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Michael A. Levi, Elizabeth C. Economy, Shannon K. O'Neil, and Adam Segal

Energy Innovation

Driving Technology Competition and Cooperation Among the U.S., China, India, and Brazil

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Acronyms

ADB	Asian Development Bank
BHEL	Bharat Heavy Electricals Ltd.
BNDES	National Bank for Social and Economic Development
CBTE	Brazilian Bioethanol Science and Technology Laboratory
CCS	carbon capture and sequestration
CIC	climate innovation center
CNOOC	China National Offshore Oil Corporation
CSP	concentrated solar power
CTC	Center for Sugarcane Technology
CWET	Center for Wind Energy Technology
EMBRAPA	Brazilian Agricultural Research Corporation
EV	electric vehicle
Ex-Im Bank	Export-Import Bank of the United States
FINEP	Brazilian Innovation Agency
FIPB	Foreign Investment Promotion Board
FNDCT	Scientific and Technological Development Fund
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPR	intellectual property rights
MOST	Ministry of Science and Technology
NDRC	National Development and Reform Commission
NREL	U.S. National Renewable Energy Laboratory
OECD	Organization for Economic Cooperation and Development

OPIC	Overseas Private Investment Corporation
Pro-Alcool	National Alcohol Program
PROINFA	Programa de Incentivo às Fontes Alternativas de Energia Elétrica
PV	photovoltaics
R&D	research and development
RR	RoundUp Ready
SIPS	Special Incentive Package Scheme
SOE	state-owned enterprise
TRIPS	Agreement on Trade-Related Aspects of Intellectual Property Rights
UNFCCC	United Nations Framework Convention on Climate Change
USDA	U.S. Department of Agriculture
USTDA	U.S. Trade and Development Agency
WTO	World Trade Organization

Executive Summary

If governments are to respond effectively to the challenge of climate change, they will need to ramp up their support for innovation in low-carbon technologies and make sure that the resulting developments are diffused and adopted quickly. Yet for the United States, there is a tension inherent in these goals: the country's interests in encouraging the spread of technology can clash with its efforts to strengthen its own economy. Of particular importance is the spread of low-carbon technologies from the United States to the major emerging economies—China, India, and Brazil. Washington's strategy to promote the spread of low-carbon technologies to these countries must combine efforts to grow and open markets for low-carbon technologies with active support for accelerating the innovation and diffusion of these technologies. Its strategy will also need to reflect the unique challenges presented by each of the three countries.

LINKING TECHNOLOGY DEVELOPMENT TO DEPLOYMENT

U.S. policymakers must first understand that the relationship between efforts to develop low-carbon technologies and efforts to deploy them is complex, uneven, and varies by country. China, for its part, is pursuing a low-carbon technology strategy that is driven largely by a desire to field world-leading clean energy industries. Yet this does not necessarily mean that these same technologies will be deployed domestically. Indeed, the Chinese government does not appear to have a coherent strategy tying the country's efforts in the low-carbon technology sector to domestic emission reductions. That said, there are exceptions: Chinese efforts to develop wind technology, for example, are closely tied to initiatives that promote their domestic deployment. India, in contrast,

has prioritized addressing energy scarcity over enhancing its own competitiveness in low-carbon technologies and, as a result, is more open to foreign technology. Many Indian businesspeople have, however, lobbied for the creation of strong domestic markets for low-carbon technology, seeing them as a platform for eventual exports. This attitude has recently started to influence official policy, with the Indian government aiming to use its new drive to deploy solar technology at home as a way to boost its domestic solar businesses. Like India, Brazil is focusing more on addressing domestic challenges—in its case, those to do with energy, agriculture, and deforestation—than on building new low-carbon industries. Like China, though, it often places political importance on using domestic resources to solve these challenges. This means that Brazil's ability to solve emissions problems with domestic technology is an important contributor to its willingness to confront those problems in the first place.

GOVERNMENT POLICIES

If the United States is to influence the policies of emerging economies, U.S. policymakers will need to understand how those countries' policies—including creating markets, investing in innovation, protecting intellectual property rights (IPR), and erecting trade and investment barriers—affect their ability to absorb foreign technology.

Creating markets for low-carbon options can promote innovation and technology transfer as firms seek to meet demand. (Technology transfer, as used in this report, is the process through which countries acquire the ability to produce previously foreign technologies.) But China, India, and Brazil have not yet put in place programs to incentivize the deployment of low-carbon technologies on a scale commensurate with the challenge posed by climate change. All of them do, however, have significant programs. China has a host of efforts in a range of economic sectors. The Indian government has tried to promote low-carbon technologies, but its initiatives have generally been less ambitious. Brazil has pursued strong efforts but only in targeted areas, most notably, ethanol and agriculture.

When a country invests in innovation, it also increases its capacity to absorb technology and creates valuable partners for technology cooperation. In most areas of innovation, it is China again that leads the

pack. Yet as a clean energy technology innovator, it remains behind the curve, with most of its successes having to do with process rather than product innovation and affecting the less technologically advanced parts of the supply chain. India has invested less aggressively in energy innovation than China, a decision that mirrors a pattern seen across most of its high-tech industries, and has had difficulty scaling up its innovations. Brazil, meanwhile, boasts a state-led innovation system that, in many ways, is better developed than those in China or India. But when it comes to low-carbon technology, it focuses on first-generation ethanol and on agriculture, while innovation at the cutting edge, such as in second-generation biofuels, is limited.

The vigorous protection of intellectual property rights also promotes greater technology absorption by encouraging firms to grant others access to their intellectual property. For many years, China has shown limited inclination to protect IPR. Indeed, problems in China may be getting worse, with state-led efforts to promote "indigenous innovation" taking pressure off the government to reform its enforcement of IPR. The situation in India is considerably better: most foreign firms worry more about problems with specific companies than about the overall system. Big Indian companies, in particular, face far fewer difficulties accessing intellectual property than do smaller firms. Brazil, meanwhile, has taken what it likes to call a pragmatic approach to intellectual property rights, generally supporting their protection while carving out what it sees as public-good exceptions. Despite the perceived limits to IPR protection in Brazil and India, however, most people in those countries, particularly in business, do not view problems with IPR as a major barrier to the development or adoption of low-carbon technologies.

For the most part, barriers to trade and investment in low-carbon technologies slow the spread of technology. China has imposed a host of such barriers in an attempt to promote domestic technology and manufacturing. The country's recent emphasis on indigenous innovation, with government procurement rules and standards that favor domestic intellectual property, will intensify this tendency. Indian policies regarding trade and investment in clean energy are more open, but they still include significant barriers, particularly in trade. The approach is mixed, with, for example, new concessions over equipment for solar panel production facilities alongside new domestic content requirements for highly efficient coal-fired power plants. But

overall, India's openness to foreign investment remains robust. Brazil is perhaps the most open of the three countries. Although its tariffs are higher than the Organization for Economic Cooperation and Development (OECD) average, substantial parts of the clean energy sector have recently begun to open themselves up to foreign investment. And the state still uses its development bank to subsidize foreign firms that produce domestically, which encourages countries to transfer their technology into Brazil.

INDUSTRIAL STRUCTURE

The overall economic structure of each major emerging-economy country also has significant consequences for the scale and speed of technology transfer and diffusion—and for the potential effectiveness of various U.S. strategies. The Chinese economy is dominated by large and often lumbering state-owned enterprises (SOEs). With almost unlimited access to capital, SOEs are moving into the clean energy sector, and they will likely dominate it. Such investment brings enormous resources to the sector, but it tends to crowd out smaller and potentially more innovative technology producers. The top-down, balkanized nature of the Chinese economy also contributes to inefficiencies in the clean energy sector, which are responsible for problems of overcapacity and quality control. Moreover, by promoting duplication and by hampering learning within industries, this structure can reduce the "bang for the buck" of investment in technological innovation. Weak early-stage financial services are also a barrier to commercial technology transfer, with the relevant Chinese industries far less developed than their U.S. counterparts. They are, however, steadily improving.

The Indian economy is far more flexible, yet its industrial structure also creates important barriers to the flow of technology. The landscape is dominated by large private conglomerates. These firms have deep pockets and bring a recognized brand to what still is not a mainstream product, allowing for much-needed experimentation. At the same time, they are inevitably less nimble and have longer decision-making cycles than small start-ups; they also tend to harbor a bias toward developing technology internally over acquiring it from the outside and have had difficulty translating inventions from ideas to commercial products. That said, small players, supported by a growing

group of early-stage investors (many of them American), are becoming more prominent in India.

Brazil boasts many companies that have obtained and adapted advanced clean energy technologies. For decades, it has attracted large multinational corporations and, with them, important technologies. Yet there are structural limitations to Brazil's ability to create and absorb technology. The country has faced challenges commercializing inventions: while it is a recognized leader in clean energy such as biofuels, it has made less progress developing widely adopted products in other areas. In part, this situation results from the disconnect between research, largely done in academia, and the private sector. State institutions have stepped in to finance more innovation, but these efforts have found mixed success.

LOW-CARBON EXPORTS

The spread of technology to the major emerging economies can ultimately allow these countries to export their own clean energy innovations, which, in turn, can provide the United States with lower-cost options for solving clean energy problems at home. But exports can also present competition for U.S. firms, including in third country markets. Each of the three countries has a characteristic approach to low-carbon exports.

China views its clean energy industry as capable of playing a leading role in the global marketplace. Chinese leaders have designated clean energy a "strategic new industry," and the Ministry of Commerce is aggressively promoting Chinese clean technology exports. China's efforts are focused first on markets in developing countries, but the sector is also eager to penetrate markets in developed countries, as it has successfully done with solar technology. These efforts, however, are limited by shortfalls in quality control.

Indian companies are also confident in their ability to compete with, and bring technology to, other emerging economies, but are less focused on markets in developed countries. They see their major competitor as China, not the United States. Still, Indian firms are also interested in developed countries, building on the success of the wind power company Suzlon and the automobile manufacturer Tata. People speak of leveraging India's strength in information technology, systems

engineering, and mechanical engineering to produce globally viable technologies in smart grids, green buildings, and concentrated solar thermal power.

As the world's largest exporter of biofuels, Brazil is already a leader in the clean energy trade. It has aspirations to substantially increase its exports of low-carbon technology—such as genetically engineered sugarcane plants, high-efficiency milling technology, and technology for flex-fuel cars—primarily to other developing countries but also, if possible, to developed countries. With all of these technologies, though, Brazil has made exporting internationally a secondary priority to producing for domestic markets.

U.S. POLICY ANALYSIS AND RECOMMENDATIONS

The link between domestic technology development and deployment in the major emerging economies means that the United States can often encourage emissions reductions by promoting the spread of low-carbon technology to those countries. At the same time, the range of wise policy options will be limited by the need to preserve U.S. competitiveness.

The United States should encourage the major emerging economies to become more open to the commercial transfer of low-carbon technology while also actively promoting the spread of technology itself. If barriers to trade and investment were reduced and IPR protection strengthened, markets for low-carbon technologies would be enlarged—which would help address U.S. firms' and workers' commercial concerns. Actively promoting technology transfer, meanwhile, would help reassure developing countries that their own firms would also stand to gain. These two approaches—commercial openness and active promotion of technology transfer—would also reinforce each other environmentally, since both, done right, would accelerate the innovation, diffusion, and deployment of low-carbon technologies. If, however, a particular country adopted a persistently closed approach to the commercial flow of technology, it would be unwise for the United States to blindly persist in actively promoting technology transfer to it. Doing so would reduce incentives for the country to open up in the first place and undermine the essential support from U.S. firms and workers for the strategy. Similarly, if a country fails to make progress

on openness to commercial technology flows, the United States should pull back on technology cooperation, thus avoiding being exploited.

INVEST IN INNOVATION AT HOME

The United States must start its strategy by strengthening its own system for low-carbon innovation. The pace of innovation in low-carbon technology, both in the United States and abroad, is too slow given the challenge climate change poses. The United States should create large domestic markets for low-carbon products and services, which would encourage private innovation. It should also support innovation directly by funding research and development (R&D) for low-carbon technology, as well as projects that demonstrate various technologies' feasibility, at a greater scale than it currently does. And it should adopt policies that encourage investors to finance companies through the period in which they (or someone else) have invented a product but not yet commercialized it—the so-called "valley of death."

ENCOURAGE AN OPEN INTERNATIONAL SYSTEM FOR LOW-CARBON INNOVATION AND DIFFUSION

Openness to foreign technology tends to accelerate the innovation and diffusion of low-carbon technology and reduce costs for all involved. The United States should thus actively promote openness at all phases of the innovation process as it tries to create demand for low-carbon technology in the major emerging economies. But it should also be sensitive to the fact that some limited protections may be necessary to build domestic political support for policies that increase demand for low-carbon options.

U.S. policy should encourage the major emerging economies, particularly China, to better protect IPR, while guarding against abuses by firms with dangerously large market shares and the ability to monopolize markets for specific technologies. Any necessary adjustments to rules about IPR should be made deliberately and cooperatively, rather than through the weak enforcement of accepted laws.

The United States should also promote cross-border investment. It should encourage India and Brazil to maintain their largely open approaches. The case in China is more complex: Washington should press Beijing to relax its restrictions, and it should withhold some of

its support for policies that speed the spread of technology if Chinese investment and trade barriers are so high that U.S. low-carbon innovators do not stand to benefit from a deal.

All three major emerging economies are imposing significant barriers to trade in low-carbon technologies, which slow down the spread of technology and close off commercial opportunities for U.S. firms. The United States should push back, targeting barriers that not only hurt commercial interests but also delay the adoption of low-carbon technology. It should be willing, however, to tolerate limited trade barriers that the governments of emerging economies need to build political support for emissions-cutting policies. (U.S. policymakers will need to decide what category individual measures fall into on a case-by-case basis, based on their understanding of the relevant political dynamics.) U.S. policy should also attempt to harmonize standards for low-carbon technologies with those of other major producers.

The United States also needs to guard against unfair competition. It should, of course, welcome foreign goods and capital in clean energy projects when their presence arises from genuine comparative advantage. If, however, foreign firms are playing an outsized role because their home countries have adopted unfair industrial policies, it may be prudent to limit their participation in taxpayer-supported projects. While there is a strong element of judgment involved in distinguishing the two cases, the United States should be guided first by whether countries' actions are consistent with their World Trade Organization (WTO) obligations. India and Brazil, so long as their policies do not change considerably, are unlikely to be affected by such an approach. But China may present greater challenges. As for selling low-carbon technologies (or the companies that own them) to major emerging economies, the United States should reassure these countries that it will not block the sale of such technologies to them unless doing so would compromise military secrets or allow a critical market to be cornered.

ACTIVELY PROMOTE TECHNOLOGY DIFFUSION

Openness alone is not enough. Technology has to be actively pushed out into emerging economies throughout the innovation process—from R&D, through demonstration and commercialization, to diffusion and deployment. The United States should, however, withhold

certain elements of support for cooperation when dealing with countries that refuse to adopt open and cooperative approaches themselves.

As part of this effort, the United States should support joint and coordinated programs for low-carbon R&D with China, India, and Brazil. It has already taken some steps to strengthen joint R&D, establishing the U.S.-China Clean Energy Research Center and the U.S.-India Joint Research Center, and individual U.S. government researchers often cooperate with scientists in the major emerging economies. Washington should increase its financial support for collaborative R&D and establish a third joint center with Brazil that would focus on biofuels and agriculture. Domestically, R&D should be designed with an eye toward applications in the major emerging economies.

U.S. policy must also address IPR. Currently, the cost of patents is only a small part of the cost of most low-carbon technologies, so reducing the price of patents makes little sense. The United States should, nonetheless, pursue policies that address companies' willingness to license technology. It should provide IPR insurance for small and medium-sized enterprises, though only in cooperation with countries that have not adopted hostile approaches to IPR. It should be extremely cautious, though, when it comes to compulsory licensing of technologies, which has often been demanded by developing countries. Compulsory licensing will usually hurt U.S. firms while failing to promote meaningful technology transfer, since the owner of a technology will likely refuse to cooperate. Moreover, other countries could abuse compulsory licensing to appropriate intellectual property. There may, however, be extreme and currently unforeseen circumstances in which compulsory licensing is appropriate. Indeed, the major emerging economies already have recourse to compulsory licensing under certain conditions under the WTO Agreement on Trade-Related Aspects of Intellectual Property (TRIPS). The United States should work with those countries to discourage compulsory licensing except, possibly, in cases involving gross abuse of market power.

Just as government support is needed to help inventions cross the valley of death between invention and commercialization in the United States, government efforts are also needed to aid commercialization internationally. The United States should support demonstration projects for low-carbon technologies in the major emerging economies, especially if a technology is likely to play a major role in a particular

major emerging economy and faces significant barriers at the demonstration stage. U.S. investment, however, should concentrate on the sectors in which countries have shown a commitment to expanding demand and an openness to foreign technology.

Since financing cross-border commercialization can create competitors for U.S. firms, several essential precautions must be taken. The United States should emphasize efforts with India and Brazil, where the likelihood of creating competitors is lower, because those countries and their firms have generally been less aggressive and successful in promoting exports to developed-country markets. The United States should target its support to those areas in which the deployment of technology would be heavily delayed if U.S. firms exclusively were allowed to commercialize the technology. It should emphasize continued market access for U.S. companies to countries it cooperates with. Finally, it should insist that emerging-economy governments significantly cofinance investment.

In promoting the spread of technology, Washington should also encourage greater contact between different players in the technology sector. The United States has extensive consulting and financial services industries that connect entrepreneurs and companies, whereas in the major emerging economies, these industries are considerably less developed. Given the disparity, the United States should help U.S. firms and innovators better navigate the major emerging economies by strengthening the Department of Commerce's existing efforts on this front. It should also support extension centers that connect U.S. inventors with foreign entrepreneurs and firms that could commercialize the ideas in the major emerging economies. (Such a program would build on India's proposed "Climate Innovation Centers.")

Finally, the U.S. government should use financial support for U.S. technology exporters to shape the policies of emerging economies. Both the Export-Import Bank of the United States (Ex-Im) and the Overseas Private Investment Corporation (OPIC) have outlined embryonic strategies for promoting low-carbon technologies abroad. Neither institution, however, works aggressively to promote policy changes. Nor does either provide additional funds to close the gap in expense between low-carbon technologies and more polluting options. If a target country is taking steps to build robust low-carbon markets and opening up to commercial technology flows, Ex-Im should provide preferential

financing that helps low-carbon options compete with fossil fuels, and OPIC should provide insurance against the risk that those markets will not materialize due to policy failures. The United States should only take such steps, however, if its counterparts are doing their part to create a hospitable environment for commercial technology flows.

Low-Carbon Technology in the Major Emerging Economies

Scholars and policymakers have devoted relatively little attention to understanding how low-carbon technologies actually spread. Who is likely to create and commercialize new low-carbon technologies? What are the mechanisms through which low-carbon technologies developed in one country get produced or adopted in others? How do countries' positions as inventors and manufacturers of low-carbon technologies affect their willingness to encourage stronger action on climate change? And how can a better understanding of the dynamics of technology flows be used to craft a more effective response to climate change?

These questions have been part of a long-standing and largely unproductive debate over "technology transfer" within international negotiations about climate change. The centerpiece has been a fight over the treatment of intellectual property rights (IPR) in any international climate regime.[1] The governments of developing countries have insisted on concessionary approaches to IPR for low-carbon technologies—that is, schemes that would transfer technology at significantly reduced prices or without the consent of patent holders. They point to the precedent set with HIV/AIDS drugs to contend that, since climate change is a global emergency, IPR barriers to the spread of climate-friendly technologies must be removed. The governments and businesses of developed countries have pushed back forcefully. They argue that weakening IPR would remove the incentives for firms to develop new low-carbon technologies. They also worry that weak IPR protection would cut into businesses' profits. The very mention of the phrase "technology transfer" sends them running for cover.

This combination of controversy and stalemate has consigned technology transfer to the back burner of many climate policy discussions. But the forces that shape technology flows extend far beyond IPR. Indeed, policymakers and negotiators have begun to broaden the scope of their discussions about technology transfer in the last two years,

focusing in particular on concrete technology cooperation. Yet there are still big differences among the important players: everyone agrees that technology must diffuse rapidly, but there is widespread disagreement on how to encourage that diffusion.

The United States needs a new approach to international technology policy as part of its strategy for dealing with climate change. Policymakers must move beyond traditional notions of technology transfer and shape an environment that accelerates innovation and the diffusion of low-carbon technologies globally, while respecting (and even leveraging) countries' real concerns about international competitiveness.

That challenge is the focus of this study. Specifically, we explore the spread of low-carbon technologies from the United States to the major emerging economies: China, India, and Brazil. The first section of this report analyzes the strategic, economic, and environmental contexts for low-carbon technology development and diffusion in these countries before assessing how the policy and business environments in each affect technology flows. The second section evaluates an array of policy options against that reality and U.S. economic interests, and recommends an agenda for the United States. An appendix presents a series of case studies on specific low-carbon industries in the three countries that inform the rest of the report.

WHAT DO WE KNOW ABOUT TECHNOLOGY FLOWS?

This study focuses on understanding the broad range of mechanisms through which technology spreads across borders and on the policy tools with which the United States can accelerate that spread. These mechanisms include sharing knowledge that allows countries to create or deploy new technologies themselves and trading in goods and services that use new technologies. Technology can spread between governments, as with cooperative R&D led by government labs; between firms, as with joint ventures, the sale of goods, or the licensing of patents; or within firms, as with foreign direct investment.

When it comes to U.S. policy options, we restrict ourselves to considering policies that affect technology flows directly rather than incidentally. We are interested, for example, in policies that subsidize the sale of U.S. solar panels to India, since they specifically encourage solar

technology to move between countries or U.S. companies to license solar technology to Indian firms. (In both cases, solar technology is moving between two countries.) We are not, however, interested in U.S. policies that would finance the adoption of solar energy in India more generally, or in broader diplomatic strategies that would pressure India to mandate the use of solar power.[2] Such tools have critical roles to play in climate policy and have been studied extensively, including by authors who consider them to be a central element of what they consider technology transfer policy, but they are beyond the scope of this investigation.

We define technology transfer as the process through which countries (or, more precisely, their firms) acquire the ability to produce previously foreign technologies. This is distinct from cross-border sale of the same products, which provides another way that countries can access low-carbon options. Both processes contribute to technology diffusion.

Most careful analyses have largely dismissed the value of strategies that focus on directly encouraging the spread (not just sale) of technology, arguing that such an approach is wanting on both environmental and commercial grounds. Many authors have found few major barriers to the spread of low-carbon technologies (other than a lack of demand) and thus little potential environmental gain from addressing any barriers.[3] Patents for most classes of low-carbon technologies, those authors emphasize, are widely available today, and patent fees are usually only a small part of the cost of implementing those technologies.

Yet in arguing against strategies that directly promote the spread of technology , these studies tend to miss four potentially critical issues. First, by focusing on whether technology flows have been sufficient to meet demand for low-carbon technologies in the past, they miss the possibility that the spread of technology may itself be able to spur demand. Second, by fixating on whether technology transfer does or does not happen, they ignore the equally important question of how quickly it happens. This is particularly relevant if time-bound goals for emissions reductions are to be met. Third, they treat the energy-technology world as static when, in reality, in order to cut global emissions, the intensity of innovation in low-carbon technology will need to be greatly increased. That, in turn, could lead to much greater government involvement in energy technology, and hence force government to become more involved in decisions about technology flows; in addition, greater investment in innovation could in principle lead to technologies whose patents are much more costly. Fourth, they tend to

focus on barriers to technology flows (such as weak IPR protection or high tariffs) and thus miss the potential value of other measures that would actively encourage technology transfer, such as collaboration on demonstration projects.

The case against direct U.S. government promotion of technology transfer on commercial grounds is flawed, too. Many observers focus on the compulsory licensing of intellectual property and thus see a zero-sum game that U.S. companies can only lose. There are, however, at least five ways in which government-driven technology transfer might directly improve the bottom lines of U.S. businesses. First, technology transfer might directly expand markets for U.S. firms. This might be the case, for example, if the United States helped another country acquire technology for integrating intermittent renewable energy supplies into its power grid, which, in turn, increased commercial demand from that country for imports of wind and solar power equipment. Second, technology transfer might help U.S. inventors commercialize technologies abroad that might not have applications at home. U.S.-invented technologies that improve solar water heaters, for example, are unlikely to receive much interest from firms that manufacture for the U.S. market, but they could be of great interest to firms whose customers are in the developing world. Third, since technology transfer can encourage recipient countries to impose regulations that provide incentives for adopting both domestic and foreign low-carbon technologies, U.S. firms may be able to capitalize on the new markets. Fourth, technology transfer may accelerate innovation; the rapid spread of technology allows more people and firms to more quickly build upon past advances. Fifth, the spread of technology may lower costs for U.S. consumers. If firms in developing countries can manufacture technologies much more cheaply than their U.S. counterparts, all sides may stand to gain from transferring technology overseas.

For all these reasons, then, reflexive opposition to government involvement in technology transfer is mistaken. Unfortunately, with a few notable exceptions, those who have argued in favor of such policies have been misguided, too.[4] In most cases, they have ignored deep concerns about national competitiveness and thus recommended policies that, although they may accelerate the spread of technology in theory, are politically unrealistic.[5] A few authors have attempted to find win-win approaches that appeal to commercial interests of both technology providers and recipients, but the scope of their suggestions has been

limited.[6] Another cluster of studies has looked at how technology flows within specific low-carbon industries, without attempting to divine the broader policy implications (though again there are exceptions).[7] Our study builds upon all those efforts by exploring a wider set of channels through which technology spreads.

EMISSIONS CHALLENGES AND TECHNOLOGY SOLUTIONS

China, India, and Brazil are the three largest energy users and greenhouse gas emitters in the developing world. Each faces starkly different challenges and incentives.

Chinese energy consumption is expected to nearly double between 2007 and 2030, driven by the population's massive urbanization.[8] As four hundred million people move into cities, they will use more energy in their homes and drive more cars. The Chinese government is overwhelmingly focused on delivering that energy in a way that maximizes economic growth and employment, while keeping inflation under control. Its approach is also shaped by concerns about the security of its energy supply: in 2008, China imported about half of its oil, and in 2009, it became a net coal importer.[9] Chinese policymakers are, in addition, increasingly sensitive to concerns about urban air pollution, which is caused by power plants and factories that burn coal, as well as by emissions from vehicles.

For the indefinite future, China is expected to continue generating the bulk of its energy from coal and oil. The International Energy Agency (IEA) projects that between 2007 and 2030, Chinese emissions will increase by 90 percent.[10] Low-carbon energy is expected to play an increasing role in electricity generation—the IEA projects that nonfossil generation will more than triple by 2030—but coal is still expected to dominate, accounting for three-quarters of delivered electricity. Chinese cars and trucks, meanwhile, are becoming more efficient, but the demand for oil they collectively use is still expected to more than triple.

Chinese energy consumption and greenhouse gas emissions will need to be considerably lower if the world is to stabilize greenhouse gas concentrations at safe levels. The IEA has presented a "450 Scenario" that models one plausible route to the stabilization of global greenhouse gas concentrations at relatively safe levels. That scenario envisions China

reducing its emissions in 2030 to 61 percent of what they otherwise would have been, which would leave Chinese emissions only 16 percent higher than their 2007 level.[11] Achieving that goal would require greatly improving energy efficiency along with shifting from coal-fired power generation to renewable and nuclear energy. China would also need to radically improve the performance of its cars and trucks: according to the IEA scenario, nearly 40 percent of new Chinese passenger vehicles would need to be electric or plug-in hybrid electric by 2030, and other new vehicles would need to be dramatically more efficient. Just where emissions reductions come from, of course, depends on the model used to predict future energy decisions. McKinsey & Company, for example, has looked at an alternative scenario that sees Chinese emissions reduced to 56 percent of their expected level in 2030.[12] It foresees considerably smaller savings from energy efficiency than in the IEA scenario, but bigger gains from wind, solar, and nuclear power.

India has a different set of energy challenges from China. The country faces an extreme scarcity of energy. According to the World Bank, 40 percent of Indians have no access to electricity, and close to 75 percent of rural households rely on firewood for cooking.[13] Energy scarcity is increasingly seen as both an economic and political challenge: in the run-up to the 2009 election, the Congress Party promised that rural electrification would be of the "highest priority."[14] At the same time, India is increasing its energy consumption, a trend driven by urbanization and the country's growing transportation and manufacturing sectors. Coal provides approximately 40 percent of India's energy needs, and imports of both coal (currently, 14 percent) and oil (about 75 percent) are rising.[15] India now ranks fifth in carbon emissions from energy use, accounting for approximately 5 percent of the world total; the IEA estimates that this share will rise to 8 percent by 2030.[16] Per capita emissions, however, remain low, at one ton per year, compared to twenty in the United States and five in China.

The IEA projects that by 2030, Indian emissions from energy use will increase 160 percent from 2007 levels.[17] This increase would leave India with emissions roughly 30 percent those of China and 60 percent those of the United States. The IEA's "450 Scenario" envisions Indian emissions in 2030 at only 65 percent of what they otherwise would have been (but still 69 percent higher than 2007 levels). Achieving that goal would require similar shifts to those that would be needed in China. Nuclear energy, for example, would have to contribute 144 percent more than

it is currently expected to in 2030, and fifteen times more than it does today; hydroelectric power would also have to more than double relative to the baseline case and quadruple relative to today. Electric and plug-in hybrid vehicles would not need to make inroads as much as they would in China, but they would still have to constitute 20 percent of new Indian passenger vehicles by 2030. Indian industry, meanwhile, would need to drop its emissions by 16 percent relative to what they otherwise would have been.

Brazil presents a fundamentally different situation from either China or India. It has one of the cleanest energy systems in the world: electricity generation is dominated by hydroelectric power, which generates 85 percent of the country's power, while fossil fuels make up only 9 percent.[18] Transportation emissions are held in check by the widespread use of ethanol, which constitutes 40 percent of the fuel used by cars and light trucks and 20 percent of total transportation fuel.[19] It is unlikely that energy use in Brazil will be a major contributor to global emissions in the next two decades. That said, Brazil faces significant energy challenges on its horizon. As the Brazilian economy is growing, energy consumption is quickly increasing: electricity demand is expected to rise by nearly 6 percent a year through 2019, according to the Brazilian Ministry of Mines and Energy.[20] Moreover, Brazil's energy system may get dirtier soon. The government has approved several coal plants to stave off near-term power shortages, and if it is unable to meet its medium-term goals for increasing hydroelectric, nuclear, and wind power, the main alternative will be coal. Brazil's recent oil discoveries could also color its approach to energy. In 2007, Brazil made the first of several large discoveries, which are equivalent to an estimated fifty to eighty billion barrels of oil and which promise to turn the country into a major oil and gas producer.[21] They may also lead Brazil to increase the role of traditional fossil fuels in its energy portfolio, particularly to power heavy industry, in ways that current projections do not account for; they could reduce pressure to reduce oil use elsewhere in the economy.[22]

Brazil's biggest emissions challenges and opportunities are anchored in land use and agriculture; those emissions are what rank it among the biggest emitters in the world. In 2005, more than half of Brazil's emissions came from deforestation, and another quarter came from agriculture; their combined share is expected to remain roughly the same over the next two decades.[23] (Deforestation generates emissions as carbon stored in trees and soil is released; agriculture generates emissions

through releases of carbon from soil, fertilizer use, and methane from livestock.) According to McKinsey, nearly three-quarters of the cost-effective opportunities for emissions reductions in Brazil through 2030 lie in forests, with another 14 percent coming from agriculture. In many cases, these opportunities involve behavioral changes, such as reducing forest clearing or managing pastures differently, none of which require special technology. In other cases, though, technology is crucial. To lower emissions from cattle ranching, for example, feed supplements and vaccines might be used. Pressure on forests, meanwhile, can be lessened by using technology such as higher-yield seeds to increase agricultural and ranching productivity.

THE TECHNOLOGY PRODUCTION-DEPLOYMENT RELATIONSHIP

Also facing big emissions-cutting challenges is, of course, the United States, where political strategists have aimed to forge a strong relationship between efforts to develop low-carbon technologies and efforts to deploy them. Politicians are increasingly attempting to sell the need to deploy low-carbon technologies (whether through carbon pricing, traditional regulation, or tax incentives) as critical to protecting U.S. competitiveness and creating new jobs. There is also an unstated assumption that if the United States becomes a low-carbon technology leader, it would be willing to promote low-carbon technologies at home and hence reduce its own emissions. A similar dynamic could, in theory, drive other countries' choices about deploying clean energy technologies. If so, the United States might be able to leverage that dynamic to promote emissions cuts elsewhere. The political relationship between the production of clean energy technology and its deployment in China, India, and Brazil appears to be significantly weaker than in the United States.

There is a strong techno-nationalist bent to China's policy decisions. The Chinese government, however, does not appear to have a coherent economy-wide strategy that ties its leadership in low-carbon technology to domestic emission reductions. As one politically connected Chinese academic noted in an interview, China has a low-carbon technological strategy and a low-carbon economic strategy, but these two strategies do not appear to be closely connected. The country's low-carbon

technology strategy is driven in large part by a desire to become a world leader in clean energy. This does not, however, necessarily translate into domestic deployment of those technologies. The powerful Chinese solar photovoltaic industry, for example, has been built almost entirely on the back of foreign demand. Chinese investments in carbon capture and sequestration (CCS) demonstration, meanwhile, do not appear to be accompanied by any actual interest in deploying the technology on an environmentally meaningful scale (which is understandable from a purely economic and energy security standpoint). That said, there are examples to the contrary: the Chinese wind industry has been built entirely through domestic demand, and Chinese high-speed rail manufacturers started out with a domestic focus. They later attracted foreign producers and turned to overseas markets (using technologies they had adapted from their foreign partners).[24] Moreover, there can be unexpected political connections between production and deployment: Chinese solar panel manufacturers, for example, reportedly pressed the Chinese government to increase mandates and incentives for domestic solar power, arguing that otherwise, the government would be hit with antidumping suits in Europe.[25]

India's approach to low-carbon technology has been consistently less techno-nationalist than China's. Almost all of our interviewees spoke first of energy scarcity and then addressed competitiveness issues secondarily. As one manager told us, "each business finds its own technology in its own way, not like China with a strategic view. China has much more of concern about 'not made here.'" When one official was asked whether job creation was a significant incentive for boosting clean energy, he laughed, pointing out how few jobs clean energy could create relative to the country's number of unemployed.

However, a number of Indian entrepreneurs and managers spoke of the need for a close relationship between domestic and foreign markets, with one of them arguing that India could never be a "global player without a domestic market." Indeed, many Indian businesspeople and policymakers expressed a desire to have at least part of the push for new energy technologies serve other economic and technological goals. The National Solar Mission, in particular, states that its objective is to take "a global leadership role in solar manufacturing (across the value chain) of leading edge solar technologies."[26] And between the time that the National Solar Mission was announced and the date that its rules were issued, Indian solar cell and module manufacturers lobbied hard and

successfully to include strong preferences for local production.[27] Other areas in which the connection between producing technology at home and deploying it domestically is strong tend to be those dominated by state-owned enterprises, like nuclear energy and advanced clean coal.

Just as India is focused first on addressing its domestic challenges, Brazil is concentrating on energy, agriculture, and forests, rather than on building new low-carbon industries. Like China, though, it places political importance on delivering responses to its challenges with domestic resources. Indeed, the Brazilian government has had a long-standing active industrial policy. During the heyday of Brazil's import substitution industrialization strategy, in the 1960s and 1970s, the state was involved in nearly every sector of the economy, from commodities to finance to food provisions to manufacturing. While often dubbed "the Brazilian miracle"—gross domestic product (GDP) growth rates topped 10 percent—this period was followed by the "lost decade" of the 1980s, when economic bottlenecks and sky-high debt levels led to a decade of stagnation. Despite the boom-and-bust cycle, many of the private companies that are most competitive today owe their success in part to official state incentives and, often, direct management. This history makes policymakers more open to the idea of state involvement in the clean energy sector. Brazil's biofuels industry, for example, fits squarely into this model: it has focused almost entirely on serving domestic needs rather than on becoming a global technology leader, and it has been driven by a host of state incentives and support over the last three decades. Yet it has increasingly opened up to foreign involvement. Brazilian forestry and agricultural policy, meanwhile, is shaped by a strong emphasis on national sovereignty, which can spill over into the government's technology policy. As recently as 1998, Brazil rejected U.S.-made genetically engineered crops as "foreign monsters"; five years later, however, the government showed its pragmatic side and allowed the seeds.[28]

In all three countries, basic economics, rather than aspirations of technological leadership, often drives government efforts to produce technology domestically. All three can lower the costs of some low-carbon technologies by producing them domestically. Doing so reduces transportation costs, particularly in the case of bulky equipment. The cost of transporting wind turbine blades from afar, for example, can significantly increase the cost of wind installations, particularly the more advanced ones, which use larger blades.[29] Countries with strong preexisting mechanical engineering bases are especially well equipped

to take advantage of such opportunities. (Brazil, India, and China all have such capabilities.) Local production can also allow companies to use cheaper local labor, land, and other inputs. Many aspects of wind turbine assembly, to take that example again, are labor intensive, allowing developing countries to cut costs. To take another example, applying next-generation biofuel technology to sugarcane crops in Brazil might produce a more cost-effective option for the domestic Brazilian market than the alternative: applying that technology to U.S. crops and exporting the fuel to Brazil.

In addition, bringing production close to markets can help producers adapt their technologies for local use. (Companies are also conducting R&D closer to markets, which further aids in this process.[30]) For example, if a process called integrated gasification combined cycle (IGCC), which transforms coal into gas and then burns it, is to be deployed in India, it will need to be adapted for use with the country's low-quality (high-ash-content) coal. The Indian government has responded to that reality by pushing domestically designed IGCC technology, which, it argues, is cheaper.

By producing domestically, the proceeds of technology sales also tend to stay inside the country. This potentially lowers the net cost to the country as a whole, even if the price of the technology in question is not reduced. In China, for example, substituting domestically manufactured electric vehicles for imported electric vehicles (and for imported oil) would steer more money back into the Chinese economy.

That said, even though a country may have political reasons to indigenize a technology, it may not make economic sense to do so. A country's lack of technological capacity and skilled labor can make it prohibitively expensive to produce particular technologies. For example, had Brazil insisted on developing the technology for transgenic crops indigenously, it would have had to wait to actually use that technology since it lacked the domestic skill to develop it. Instead, by importing foreign seeds, it was able to adopt the technology quickly. Shortages of critical technological components can also make the full indigenization of a technology too slow and expensive. Chinese domestic content requirements, for example, slowed the initial adoption of supercritical coal and wind technology, since domestic suppliers experienced a shortage of important components.[31]

Insisting on domestic manufacturing for political reasons can also cause governments to forfeit the advantages that come from economies

of scale. If India, for example, insisted on producing its own silicon wafers for solar cells, it would incur far greater costs than it does importing those wafers from other countries that already manufacture large quantities of wafers, not only for solar cells but also for semiconductors. Domestic production can also be counterproductive if it requires diverting resources from more productive applications. U.S. workers, for example, generally have much more productive things to do than assemble solar panels (a low-value-added part of production). Finally, policies designed to promote domestic production can backfire if they provoke retaliation from trading partners.

GOVERNMENT POLICIES

Countries' abilities to absorb and produce foreign technology can thus influence whether they deploy that technology. We explored government policies in five areas that can affect countries' abilities to absorb foreign technology.

DEMAND FOR LOW-CARBON TECHNOLOGY

Creating markets for low-carbon technology can indirectly promote innovation and technology transfer as firms seek to meet new demand. All three emerging-economy countries studied here have put in place significant programs to encourage the deployment of low-carbon technology. Moreover, investment in new power generation in China and India will be far greater than in the United States in the coming decade; to the extent that those countries shift their generation mix toward cleaner technologies, they will be able to exert considerable leverage over clean energy technology providers.

China's leaders have been trying to restructure the country's energy consumption patterns for several decades and, in the last five years, have established a series of specific targets. Beijing has pledged to reduce energy intensity by 20 percent during 2006–2010, cut carbon intensity by 40 to 45 percent from 2005 levels by 2020, and increase nonfossil (renewable and nuclear) energy to 15 percent of total primary energy by 2020. The country is struggling to meet its 2010 target for energy intensity.[32] But officials have been much more upbeat about their ability to meet, and even exceed, their renewable energy target for 2020.[33]

These targets are backed by both investment and policy. In 2009, for example, China spent $34.6 billion on renewable energy, along with large sums on energy efficiency, clean coal, and nuclear power.[34] The Chinese leadership has adopted large-scale initiatives designed to transform the country's use of energy. There are programs to deploy electric and hybrid-electric vehicles and high-speed trains; programs to integrate energy efficient building materials and products into public, commercial, and residential construction projects; programs for making the production processes in China's most energy-intensive industries, such as cement, steel, and chemicals, much more energy efficient; and programs to ratchet up the role of renewable and nuclear energy as a source of electricity through the use of feed-in tariffs and favorable financing. These efforts have driven the transfer of relatively mature technologies into China. Westinghouse Electric Company, for example, is bringing significant parts of its nuclear technology to the country, eager to get a piece of its nuclear energy market. Japan's Kawasaki Heavy Industries, meanwhile, has brought a large amount of high-speed rail technology to China—enough that Chinese firms now appear able to stand on their own as producers by using it.[35] Neither of these decisions, though, was purely economic: technology transfer was a condition for market access.

The Indian government has also been active in promoting low-carbon technologies. It is leading an effort to make coal generation more efficient (through the near-term deployment of supercritical power plants) and to improve energy efficiency (in households, vehicles, and industry). As one senior official said, "The fact that we will continue to depend on coal is incontrovertible." The large Indian market for efficient coal generation has drawn in technology providers from Japan, China, and the United States. India's efforts regarding renewable energy have been a relatively low priority but are becoming more prominent. Renewable energy currently makes up 6 percent of total power generation, and investment in the sector rose to $3.7 billion in 2008. The Eleventh Indian Five Year Plan, which ends in 2012, has set a target of increasing the installed capacity of renewable energy (excluding large hydroelectric installations) to 23,500 megawatts—or more than 10 percent of the national total.

India's efforts to promote renewable energy provide a window into its overarching policy approach to attracting technology transfer. Wind is the most technologically advanced renewable technology in India: capacity has increased twelve-fold in the last decade, to

10.9 gigawatts, placing the country fifth worldwide as far as installed capacity, while the costs of generating wind power have halved.[36] The government has encouraged the deployment of wind turbines with instruments such as long-term low-interest loans; accelerated depreciation of capital investments in wind projects; concessions on import duties, sales taxes, and excise duties; and a ten-year income tax exemption for profits from wind generation. These efforts are complemented by an attempt to cut fossil fuel subsidies. Foreign firms have been hesitant to invest because of inconsistent incentives, but they have still brought technology to India, both to serve the domestic Indian market and for low-cost export. And with a recent shift in Indian policy that rewards more efficient turbines, foreign technology transfer is set to increase.

The Indian government has also launched a National Solar Mission, which has established a goal of 20,000 megawatts of solar generating capacity by 2022. In its first phase, the mission will use subsidies and compulsory purchases to "capture the low hanging options" in solar thermal power and promote grid-connected solar photovoltaics (PV). As costs drop, the government's support will taper off. There is considerable skepticism in India, though, over whether the target will be met. It is too early to tell how much technology transfer the growing market will incentivize.

Brazil benefits from an abundance of cheap large-scale hydroelectric power (which is largely low tech). Its other low-carbon electricity efforts have thus been relatively weak. In an effort to boost generation during the dry season (when hydroelectricity declines), Brazil has attempted to push wind into the marketplace, allowing producers to sell electricity through auctions at relatively high prices. Several foreign manufacturers have responded by beginning to build turbine manufacturing facilities in Brazil. (Until recently, Brazilian policy supported a much weaker wind market; the result was that only two firms, one from Germany and the other from Argentina, built production facilities in the country.) Brazil has also attempted to promote nuclear power, but it is increasingly looking to indigenous options rather than importing technology. In transportation, Brazil has made a massive push for ethanol (and, relatedly, for flex-fuel cars), which makes up 40 percent of fuel for passenger vehicles, taxing ethanol at a lower rate than gasoline. As with hydroelectric power, Brazil has focused on domestic technology, meaning that its large biofuels market has not translated directly into

large-scale technology transfer from abroad. Efforts to tackle deforestation—the biggest source of emissions in Brazil—are less focused on deploying new technology than on changing behavior. Nonetheless, Brazil has taken important steps in complementary areas, such as agricultural and ranching productivity. (Increased productivity in agriculture and ranching removes pressures to clear more forested land.) Rather than creating incentives or mandates for the adoption of advanced technology, the government has so far concentrated on removing obstacles to productivity growth (such as price controls and barriers to the consolidation of smaller farms) and on providing state support for R&D. These sorts of incentives can help curb emissions while also promoting economic growth. Brazil's massive agricultural markets have also made it more attractive for foreign firms to bring advanced technology to the country.

GOVERNMENT INVESTMENT IN INNOVATION

Governments that invest in innovation (whether in R&D, demonstration projects, or commercialization efforts) create the capacity to absorb technology and create valuable partners for technology cooperation. Without such support for innovation from a developing country, foreign firms are less likely to effectively bring their technology to it. On the other hand, governments that invest more in innovation can perceive a lesser need for international cooperation.

In 2009, China topped the world in total investment in renewable energy and energy efficiency (and also made huge investments in nuclear and cleaner coal). Eighty-six percent of the country's total investment of $34.6 billion, however, was for asset finance, much of which was spent deploying mature technology rather than advancing new technology.[37] China reportedly spends $39 billion on R&D, but the portion allocated to clean energy remains small.[38]

As early as the mid-1980s, Beijing identified energy technologies as one of the ten priority areas within the State High-Tech Development Plan (known as the "863 Program"), which was intended to encourage indigenous capability for innovation.[39] For the Eleventh Five Year Plan (2006–2010), the 863 Program, under the auspices of the Ministry of Science and Technology (MOST), allocated specific amounts of money for clean energy programs: $11 million per year for hydrogen and fuel cell technologies, $11 million per year for energy efficiency

technologies, $6.5 million per year for clean coal technologies, and $4 million per year for renewable energy technologies. The National Basic Research Program (known as the "973 program"), which is also administered by MOST, has supported a number of related projects, including research into China's electric grid system, large-scale nuclear fission and fusion, and coal bed methane mining.[40] The stated goal of these programs—not always borne out in practice—is not to pick winning and losing technologies but to give the riskiest ideas a chance.[41] While these figures are significant, they are still well below U.S. government spending: the U.S. Department of Energy budgeted $2.4 billion for energy-related R&D in its 2009 budget, before massive increases through the economic stimulus package of early 2009.[42]

China has also passed laws and started programs designed to enhance research, development, and early-stage deployment of renewable energy technologies and energy efficiency technologies.[43] Together, these initiatives target a wide range of products and processes, from financial support for energy-saving lamps and nuclear power to pilot projects for new energy cars.[44] Beijing has buttressed these initiatives with specific incentive and regulations to encourage R&D in the clean energy sector, such as preferential tax and financing policies and government procurement for indigenous innovation. It has allowed more R&D expenses to be deducted from taxable income, encouraged commercial banks to provide loans at discounted interest rates, provided financial support to companies that purchase indigenously innovated products, and encouraged venture capital investment with government funding.[45]

Universities, such as Tsinghua in Beijing, have become major centers of clean energy research, benefiting from both investment by the central government and partnerships with multinationals such as BP and government entities such as the European Union. In December 2009, Beijing announced the establishment of sixteen new energy R&D centers that will focus on, among other things, nuclear and wind power and high-efficiency power generation and transmission.[46]

Western journalists and analysts have written extensively about the strengths of China's emerging clean technology sector. A recent report by the Center for American Progress, "China's Clean Energy Push," captures well the sense that China has articulated a clear and coherent plan to become the world leader in clean energy innovation, manufacturing, and deployment.[47] On its face, the evidence appears compelling.

Yet China, in fact, remains behind the curve in clean energy, with most of its successes having to do with production processes rather than product innovation. Small successes in export-worthy, Chinese-patented pressure gasification technology (used in IGCC) and wind turbine technologies that can withstand typhoons, however, hint at potential growth in this area over time.[48]

China has also taken advantage of other countries' interest in international government-to-government cooperation to an extent not seen in other developing counties. In 2007, the Ministry of Science and Technology and the National Development and Reform Commission (NDRC) outlined the top five areas for international cooperation on clean energy: solar power, biomass fuels and power generation, wind power, hydrogen energy and fuel cells, and natural gas hydrates.[49] Since then, China has announced a number of partnerships—most notably with Japan and the European Union, but also at a smaller scale with the United States through efforts such as the U.S.-China Clean Energy Research Center—and concluded "Memoranda of Understanding" on specific areas of clean energy R&D with a number of countries. But it is too early to ascertain the real value of such cooperation in fostering clean-energy innovation within China.

India has invested less aggressively in energy innovation than China, a decision that mirrors a pattern seen across most of its high-tech industries. The government has set a goal of investing 2 percent of GDP in R&D by 2012. For most of the last decade, however, overall Indian investment in R&D stayed flat, hovering around 1 percent of GDP.[50] Universities have generally failed to keep pace with research needs. A 2009 government study found that the number of citations of renewable and clean energy-related research papers fell between 1995 and 2007, and only nine patents for solar energy technologies were granted in the country from 2001 to 2009. Again, the Indian government has ambitious plans: in July 2008, the Cabinet approved eight new Indian Institutes of Technology (bringing the total to fifteen), and the Planning Commission has proposed spending $760 million over seven years on seven new Indian Institutes of Management (for a total of fourteen), two additional Indian Institutes of Science and Engineering Research (for a total of five), twenty more Institutes of Information Technology, and thirty additional universities.[51]

A consistent critique of India's science and technology system is that although the system has clear instances of individual greatness,

it cannot reproduce these outcomes on a larger scale.[52] The Indian genius is what the writer Pavan Varma and others have called *jugaad* innovation—"creative improvisation" based on individual ingenuity.[53] A jugaad is a low-cost, locally built, often jury-rigged truck or car used in the countryside; in the same way that the makers of these vehicles have to improvise in the face of scarcity and shortage, Indian companies routinely overcome inadequate infrastructure and opaque government regulations. But the organizational base or support needed to move to the next level does not exist.

Wind energy provides an example. Investment in wind energy innovation has been minimal. The Indian government sponsors a Center for Wind Energy Technology (CWET), which performs product certification and testing, but its technical skills are not highly regarded by those in industry. Nonetheless, from the Indian wind energy industry's early days, the government has supported demonstration projects, such as a joint effort between the central government and the electricity board of Tamil Nadu to connect a wind farm in the state to the grid. It has also spent money mapping the country's wind resources, which can promote the deployment of wind turbines.

India has gone to another extreme with IGCC, attempting to indigenously develop methods to handle its high-ash-content coal. But this effort lags far behind technology in the rest of the world: a state-owned firm is currently trying to build a demonstration plant that generates 125 megawatts—a threshold the United States passed in 1984. A push for domestic innovation, it turns out, does not necessarily yield superior results.

India's efforts in solar energy promise to be more substantial and more carefully crafted. The government has backed an ambitious effort to reduce costs in existing technologies and foster breakthroughs with new ones. To foster the incremental innovations that are likely to come only with hands-on knowledge of the manufacturing process, in 2007 the government initiated the Special Incentive Package Scheme (SIPS), which provides 20 percent of the capital expenditure during the first ten years for semiconductor industries (including manufacturing activities related to solar PV technology) that are located in special economic zones and 25 percent of the capital expenditure for those that are not located in the zones.[54] The new Solar Mission, a government policy initiative, calls for the proactive implementation of SIPS, the development of a SIPS-like program for solar thermal energy, and soft

loans for small and medium-sized enterprises.[55] In addition, the mission outlines an R&D strategy focused first on improving efficiencies in "existing materials, devices, and applications" and then on "developing cost-effective storage technologies." This plan will likely be bolstered by the recent announcement that the government intends to levy a small fee on coal-fired electric generation and use the proceeds to support clean energy R&D.

The state-led Brazilian innovation system, after nearly a half century in the making, is in many ways better developed than that in China or India. It invests relatively little, however. R&D spending averaged 1 percent of GDP over the last decade, considerably below the OECD average of 2.3 percent and the Chinese rate of 1.5 percent.[56]

The government invests in public sector innovation efforts, particularly in ethanol and agriculture. The most recent example of this is the Brazilian Bioethanol Science and Technology Laboratory (CBTE), which was created in 2009.[57] The CTBE is a university-style campus in the state of São Paulo that will conduct R&D on all aspects of the sugarcane and ethanol cycle and will provide demonstration facilities for second-generation ethanol production. Its goal is to help researchers recognize and reduce bottlenecks while improving efficiency and productivity in the fuel market. Particularly in agricultural biotechnology, university-based research contributes to similar ends, and so does R&D and commercialization activity sponsored by the state-owned Brazilian Agricultural Research Corporation (EMBRAPA). State-owned companies, at slightly greater distance from federal control, also invest in fundamental innovation. The most prominent example is Petrobras, which has invested substantially in R&D for biofuels and in CCS.

Several government financial institutions also promote innovation in the private sector. The state-owned National Bank for Social and Economic Development (BNDES) lends over $70 billion a year at preferential rates to foreign and domestic companies. Since BNDES loans are several percentage points cheaper than going market rates, the government is providing a substantial subsidy to encourage investment. BNDES lends some $3 billion a year specifically for innovation, including in clean energy and agriculture.[58] In 2009, it was the world's largest provider of project finance to the renewable energy sector (both by the number of deals and by the total invested).[59]

Alongside the BNDES are other public avenues of financial support, including an economic subsidy program for innovative projects, and a

Scientific and Technological Development Fund (FNDCT) that funds R&D and innovation projects for the Amazon, agribusiness, biotechnology, energy, water resources, mineral, oil and natural gas. Both are led by the Brazilian Innovation Agency (FINEP) under the Ministry of Science and Technology, and are more open to small and medium-sized enterprises than BNDES is. (Some observers, however, criticize FINEP for being overly bureaucratic.[60]) Financial incentives are also offered by the National Council for Scientific and Technological Development and other institutions through direct financing, loans with more flexible payment terms, and tax exemptions. To date, these programs have spent hundreds of millions of dollars to fund innovation, much of it in low-carbon areas—in the broad scheme of low-carbon innovation, though, a tiny amount.[61]

INTELLECTUAL PROPERTY PROTECTION

Strong intellectual property protection encourages firms to allow others access to their technological knowledge, whether protected by patents or trade secrets, thereby promoting greater diffusion of technology. When IPR protections encourage firms to make their inventions public, they also help accelerate innovation, since others can build on their discoveries. By contrast, weak IPR protection can deter firms from entering new markets and discourage them from sharing their knowledge.

China has long been the focus of U.S. concerns about IPR. Although IPR laws exist in China, they are poorly implemented. While there are a number of reasons why implementation fails—little coordination among Chinese government agencies, local protectionism, corruption—a critical factor is the absence of credible criminal and administrative penalties. Courts routinely award intellectual property damages well below the actual amount of damage and are reluctant to discipline local and state owned entities. Many multinational corporations compensate for this failure by retaining significant intellectual property in countries where intellectual property safeguards are stronger. Even when they establish R&D centers in China—either to take advantage of high-quality, low-cost engineering, or in response to pressure from the Chinese government—corporations tend to focus their China-based R&D on only one element of the research.[62]

This failure to protect IPR is increasingly seen as part of a broader effort to actively promote domestic intellectual property. As Jeremie

Waterman of the U.S. Chamber of Commerce noted in his June 2010 testimony before the International Trade Commission, a weak intellectual property rights regime enables the government to "intervene in the market for IP and help its own companies 're-innovate' competing IPR as a substitute to foreign technologies."[63] Since 2006, China's National Long- and Medium-Term Program for Scientific and Technological Development has sought to achieve a high degree of "indigenous innovation." (Originally, the term in Chinese, *zizhu chuangxi*, was conceived as "autonomous innovation," which suggested control over technology as opposed to the currently favored interpretation of indigenously creating technology.[64]) By 2020, China aims to reduce its dependence on foreign technologies to 30 percent, increase the contribution of high-tech products (as opposed to manufacturing) to economic growth to 60 percent, and rank in the world's top five countries in terms of patents granted and citations used in international scientific papers.[65]

Only recently, however, have these goals been openly operationalized in a way that appears threatening to the free flow of technology across international boundaries. As Waterman notes, "Although China has long had a series of policies, laws and guidance that have encouraged foreigners to transfer technology on nonmarket terms, China has more recently begun to implement a medium- and long-term indigenous innovation plan via a growing web of discriminatory industrial policies, including in the areas of government procurement, information security, standards setting, tax, antitrust, IP protection and enforcement and industrial espionage."[66]

With this push for indigenous innovation, China will compound the weaknesses of its regulatory and enforcement regime to provide an even greater competitive advantage to its companies. This, however, comes at the potential price of foreign companies bringing their IPR to China, which could ultimately stunt Chinese innovation.

India's IPR situation is considerably better. Most foreign firms do not show the same wariness about the domestic market as they do with China; rather, their suspicions focus on specific Indian companies. Doing business with large Indian companies presents few problems, since the reputational risk associated with IPR infringement is a clear deterrent, while those looking to partner with smaller firms face larger potential problems.[67] That said, advisers to foreign businesses note that foreign companies often approach the Indian market with fears about IPR that are not supported by reality.

Most Indians, particularly those in business, do not see IPR as a major barrier to the development or adoption of low-carbon technologies.[68] An entrepreneur involved in a solar venture, for example, described acquiring IPR for photovoltaics as "very straightforward"; since China, Israel, and Germany all take part in manufacturing for the industry, there is "so much technology already out there."[69] The entrepreneur argued that the more important challenges were to drive prices down through the stabilization of markets and policies and deployment at scale. He also argued that "foreign manufacturers want to see long-term stability before they move production here."

A similar idea was expressed by an owner and operator of wind farms, who told us that "Technology access is not really a problem. Now it is just an issue of price." This notion is not unexpected, since basic wind technologies have long been off patent.[70] "Specific improvements or features" remain on patent, but the result is that there is a great deal of competition between technologies, which makes prices fall. Even when a certain technology remains patented, competition usually means that Indian firms like Tata-BP Solar can receive licenses at a reasonable price. Likewise, in reference to coal, one senior official described the problem not as one of IPR, but of access and capacity. His concern was primarily about whether foreign suppliers could actually meet Indian demand and whether an environment that enabled technology diffusion existed within India.

Brazil has taken what it likes to call a pragmatic approach to IPR.[71] It has generally been supportive of IPR but has carved out what it sees as public-good exceptions. Despite the perceived limits to IPR protection in Brazil, however, significant multinational investment has flowed into R&D-intensive manufacturing sectors, including automobiles, chemicals, computers, and telecommunications. This signals that the market is not preoccupied with this issue. Brazil's experience with clean energy is comparable, as international companies have been willing to bring their most cutting-edge technology to Brazil, provided the market justifies it.[72] Similarly, companies have been willing to bring advanced agricultural biotechnology to Brazil. Yet the means by which much investment occurs also suggests that companies do work to protect their intellectual property. Instead of using licensing agreements, many U.S. and international companies invest directly in Brazil, buying local companies or setting up their own subsidiaries. This, as opposed to licensing, provides added intellectual property protection, since the owning company

better controls the use of its intellectual property and the spread of it throughout the domestic market. Nevertheless, there are still challenges to defending IPR, often requiring negotiation with officials rather than relying on strict enforcement.[73] This gives an advantage to larger and more powerful companies, since their market weight matters more. Meanwhile, IPR protection is improving. Brazilian firms have their own intellectual property to bring to the table, and increasingly have an interest in defending these rights both domestically and internationally. Having a domestic as well as international set of interests may benefit intellectual property protections in the future by providing the domestic political incentive for the government to enforce them.

INTERNATIONAL TRADE AND INVESTMENT

Barriers to trade in low-carbon technologies (or their components) can both promote and reduce technology transfer. Barriers can reduce technology transfer by hurting sales of equipment that incorporate advanced technology and by raising the cost of components, which makes other domestically produced technologies more expensive, and thus less likely to be attractive. On the other hand, by raising the price of imported technologies, trade barriers can encourage firms to produce technologies in the countries where they will be deployed, instead of importing them. This increases some forms of technology transfer, such as through foreign direct investment.

Barriers to foreign investment in low-carbon technologies, since they limit foreign direct investment and joint ventures that bring technology with them, also discourage technology transfer. Conversely, if there is enough money to be made, these barriers can encourage firms to license technologies to local manufacturers, since the firms have no alternative way to capitalize on their intellectual property. This requires greater domestic capacity but can ultimately result in greater technology transfer, too.

China appears increasingly willing to sacrifice the economic efficiencies and environmental benefits gained from adopting foreign technologies for what it sees as the longer-term economic benefits of having its own clean energy industries. This calculation has led the country to impose a host of barriers to international trade and investment in low-carbon technology. China is in a position of unusual strength for pursuing this strategy: it is able to leverage access to its

large market and its low-cost manufacturing base to extract concessions from foreign companies.

This is in keeping with past practice; China has historically used tariffs and other trade barriers to protect its domestic producers. China's indigenous innovation strategy has also included strong domestic preferences in government procurement, which effectively impose large barriers to trade, since the state is still the dominant consumer of technology products. China also discourages trade indirectly by providing subsidies to domestic firms.[74] While this can boost the adoption of low-carbon technology in the short run by lowering prices, it can also inhibit the sort of competition and technology flows that drive down costs in the long run.

China's new emphasis on indigenous innovation has also increased the importance of standard setting. In an effort to support local manufacturers, China is seeking to replace international standards in areas such as energy efficiency with its own ones. Government procurement policies favor standards that can be met only with Chinese-controlled intellectual property. As one Chinese legislator has argued, "While foreign companies may feel their interests are hurt, everybody will be better off" if China adopts its own standards.[75] Without sustained cooperation between China and other countries to ensure compatibility across product specifications, though, the spread of technology is likely to be further impeded.

Beijing has also limited foreign investment in an attempt to strengthen Chinese-owned clean energy companies. Until recently, for example, China capped foreign participation in wind projects at 49 percent.[76] Because minority ownership weakens foreign companies' control over their intellectual property, many did not enter the market. Chinese efforts to promote investment in electric vehicles, meanwhile, will probably favor domestic firms that are based near the cities where the cars will be used. For new power plants, only Chinese firms are eligible to provide the core machinery, such as boilers, turbines, and generators. For natural gas combined cycle technology, the government has required foreign companies to transfer some of their technology to Chinese firms in exchange for the right to enter the market.

The Indian approach to trade and investment in clean energy is more open and less hostile, but it still involves significant barriers, particularly in trade. Given the ways that political rhetoric tacks between addressing energy scarcity and building industrial competitiveness, it is

not surprising that the actual policies surrounding foreign investment send mixed signals.

A number of barriers to trade exist in India, and the trend is mixed. In April 2010, the Central Electrical Authority "asked all state and central utilities to include an 'indigenous manufacturing clause' into [their] equipment contracts" for large, ultraefficient coal-fired power plants, meaning that "public utilities [will be] asked to source their equipment from domestic providers."[77] (The public sector comprised about 85 percent of the installed generation capacity in 2007–2008.[78]) For a wind turbine to pass quality control certifications, meanwhile, it effectively has to be assembled domestically, even as many parts are often imported. This problem has been reinforced by carefully designed tariff structures, which impose higher barriers to fully assembled products.

The National Solar Mission also uses tariffs to achieve specific industrial policy outcomes. The 2010 budget does allow for a concessional customs duty of 5 percent for the import of machinery required to set up photovoltaic and solar thermal power generating units. But the government (encouraged by domestic manufacturers) has issued rules that require solar cells and modules to be produced domestically for the first two years of the program, a policy that appears to be aimed at locking out Chinese and Taiwanese firms. The government has been careful, however, not to impose barriers to trade in more pure silicon and silicon wafers, the high-tech inputs for cell manufacturing, which Indian companies cannot produce.

Barriers to foreign investment in India, however, are much lower than in China. Power generation projects based on renewable energy, for example, are open to foreign investment, with automatic approval for joint ventures that have up to 74 percent foreign equity participation; for projects with 100 percent foreign equity, though, permission is required from the Foreign Investment Promotion Board (FIPB).[79] Foreign firms are also welcome in the advanced coal sector; supercritical coal plants are regularly supplied by Doosan and Toshiba. As for solar power, there do not appear to be any barriers to foreign companies setting up manufacturing facilities in India to produce cells and modules for the National Solar Mission.

Brazil is perhaps the most open of all three countries—a relatively recent distinction. A latecomer to economic liberalization, Brazil still maintains average tariffs around 10 percent, higher than the OECD

average of 4 to 6 percent.[80] In 2009 and 2010, however, tariffs on many capital goods were lowered, encouraging the importation of machinery and equipment for manufacturing and other production—a decision that removed an important hindrance to investment and increased productivity. Substantial areas of the clean energy sector have also recently begun to open themselves up. Until 2009, for example, Brazil mandated that 60 percent of wind projects' value added had to be sourced domestically.[81] Last year, Brazil lifted formal trade barriers for advanced turbines, while increasing them (temporarily, the government claims) for smaller machines. Brazil also imposed tariffs on imported ethanol until April 2010, when it eliminated those, seeking reciprocal action from other countries. As Brazil has relaxed trade barriers, however, it has also increased support for clean energy firms engaged in domestic production. Turbine manufacturers, for example, are eligible for BNDES support only if their machines are made primarily with domestic content (although foreign companies can participate).

Brazil is also relatively open to foreign investment. While large acquisitions or investments by foreign firms have occasionally prompted grumbling from more nationalistic elements in the public sector, the overall investment environment has become increasingly attractive for foreign manufacturers, financiers, and investors. With biofuels in particular, many foreign firms have recognized Brazil's resource endowments, technological strengths, and future market potential and entered the Brazilian market—on their own, with partners, or through acquisitions. These include biotech firms (Monsanto, ADM, BASF), ethanol producers (Cargill, Bunge), distributors (Shell, BP, Bunge, Amyris, Louis Dreyfus), and flex-fuel carmakers (Volkswagen, Fiat, GM, Ford, Renault, Honda, Toyota). Many of these companies' investments benefit agricultural productivity more broadly, too. In wind, Brazil has welcomed foreign direct investment and in particular the creation of local production facilities, including ones by Alstom and Siemens. This openness bodes well for the spread of technology through private market mechanisms.

UNFCCC POSITIONS

Technology transfer is regularly addressed in the UN climate negotiations under the United Nations Framework Convention on Climate Change (UNFCCC). Countries' positions in these negotiations are often poor indicators of their actual policy preferences, since these

tend to be determined more by diplomats fighting over principles than by officials who actually formulate energy or technology strategies. Indeed, while most foreign officials demand "technology transfer," most of them are hard pressed to explain precisely what they mean. Nonetheless, countries' positions do provide some indication of what they might find valuable, both substantively and politically.

China, India, and Brazil have traditionally focused their positions regarding UNFCCC technology transfer on intellectual property rights. All three have historically demanded free or compulsory licensing of low-carbon technologies. Their approaches, however, have evolved in recent years. In particular, they have focused increasingly on constructive approaches to government-driven technology cooperation, though to differing degrees.

China has deemphasized compulsory licensing in recent years.[82] Many observers speculate that this is because Chinese leaders believe that Chinese firms will control significant low-carbon intellectual property in the not-so-distant future, and they do not want other countries demanding compulsory licenses on their technologies.[83] Instead, China has pressed for the creation of an international fund (capitalized by developed countries) that would purchase private intellectual property and place it in the public domain, and provide financial support for a range of innovation activities in developing countries, including R&D, capacity building, and risk mitigation for the deployment of precommercial technologies.[84] This shift in strategy is reinforced by a growing realization in China that, in negotiations, compulsory licensing is simply not in the cards.[85]

Chinese policymakers, however, are still unsure of precisely what they want to get from UNFCCC technology negotiations. In 2009, Zou Ji, a professor of environmental policy at Renmin University and a member of China's climate negotiating team, drew up a list of forty-two technologies available in the United States, Europe, and Japan that he believed were necessary for China to achieve the goal of having its greenhouse gas emissions peak in 2030.[86] Negotiators from other countries, however, found the list unpersuasive. And China recently secured $4 million from the World Bank in order to flesh out its approach to technology transfer, but without a clear idea about what it intended to accomplish with the grant.

India shows a similar gap between rhetoric and reality in its position on technology transfer at the UNFCCC. The official bargaining position continues to insist on compulsory licensing and on flexible

approaches to IPR. At a 2009 meeting in New Delhi, Prime Minister Manmohan Singh declared, "IPR should balance rewards for innovators with the need for the common good of mankind"; he then went on to call for green technologies to be purchased through an international mechanism and distributed as global public goods.[87] But India's real attitude is more nuanced, something that is increasingly reflected in its approach to the international negotiations. One official described the stated demands as essentially a bargaining position: developing countries can be expected to raise the IPR issue in return for something else. Moreover, India has moved outside the traditional demands for technology transfer and called for setting up a global network of climate innovation centers (CICs) to enable the development and deployment of clean technology. Indeed, in the last year this has become a greater area of emphasis for Indian negotiators than traditional IPR issues. One Indian academic spoke of this as moving from technology transfer, which he saw as a meaningless notion, to innovation cooperation. Located around the world, the centers would be public-private partnerships that would draw in international expertise, focus on R&D and deployment, and meet local needs. They would drive prices down in order to speed adoption. This practical agenda is generating more enthusiasm among Indian policymakers than are the traditional battles over IPR.

Brazil has also formally supported compulsory licensing. Indeed, Brazilian officials argue more passionately for compulsory licensing than do Chinese or Indian officials.[88] Their support for such a position is reinforced by the dominance of public R&D over private R&D in the Brazilian economy, leading some to believe that IPR is of marginal importance when it comes to incentivizing innovation and technology transfer. At the same time, Brazilian negotiators appear open to other formulations, generally using the option to negotiate, successfully, better royalty rates. Unlike China and India, though, Brazil has not been proactive in proposing other approaches in the climate talks.[89]

INDUSTRIAL STRUCTURE

Public policy is not the only factor that shapes international technology flows. The overall economic structure in a developing country influences the scale and speed of technology transfer within and into that economy. We thus explored the ability and willingness of firms to absorb advanced technology in general, and foreign technology in

particular, through a variety of channels. Many of these tendencies are driven not by low-carbon technology policy but by a country's business culture and history.

The Chinese economy is dominated by large and often lumbering state-owned enterprises (SOEs). Ninety percent of commercial lending in China serves SOEs.[90] With almost unlimited access to cheap capital, SOEs are beginning to dominate the clean energy sector. For example, Gezhouba, a leading state-owned construction company, is a major player in hydropower. The China Guangdong Nuclear Power Corporation is entering the field of solar power. The Beijing-based China Ordnance Equipment Industry Group Co.—a former People's Liberation Army enterprise—has also entered the sector, embarking on an effort in wind R&D and manufacturing; thin-film solar manufacturing; and the development of new transmission, distribution, and storage technologies.[91] Such domination by SOEs tends to crowd out smaller and potentially more innovative technology producers.

The top-down, balkanized nature of the Chinese economy also causes enormous redundancies and inefficiencies in the clean energy sector. Once a mandate is announced by Beijing, every province desires its own company, which it then promotes with its own incentives and with other favored companies. This situation contributes to both overcapacity and quality control issues. And by promoting duplication and by hampering learning within industries, this structure can reduce the "bang for the buck" of investment in technological innovation. Such government-supported overcapacity is not entirely without upsides: it can make clean energy cheaper for consumers, including in the United States, at least over the short term.

Early-stage financial services are a final barrier to technology transfer in China. The Chinese venture capital and private equity industries are far less developed than their U.S. counterparts. (In 2009, Chinese investment by venture capitalists in clean technology innovation amounted to a mere 5 percent of total global clean technology venture capital.) To narrow the gap, the Chinese government is establishing its own state-owned venture capital and private equity efforts to invest domestically; in 2009, Chinese government-supported funds represented approximately 19 percent of venture capital in China.[92] Reforms are also in the works. According to Fang Xinghai, director general of Shanghai's financial services office, Shanghai may begin to allow foreign investment in yuan-denominated private equity and venture capital funds.[93]

These financial markets also focus on different parts of the innovation system than some assume: Chinese venture capitalists, for example, tend to focus on manufacturing efforts, in contrast with their U.S. counterparts, who normally take far more risk with unproven technologies.[94] Moreover, since the state dominates financial services, there is a bias toward connecting domestic partners, rather than linking technology providers with potential manufacturers and users across borders. Similarly, within the domestic economy, there is a bias toward state-owned enterprises and research institutes over private (and potentially more innovative) firms.

China has used a variety of deal structures with foreign firms in efforts that attract foreign technology. The wind sector, for example, initially emphasized joint ventures, but greater success has come through a focus on licensing technologies. As Joanna Lewis elaborates in her study of the Chinese company Goldwind's experience in wind turbines, Goldwind licensed wind turbine technology from several "somewhat second tier companies" to gain experience in a number of technologies, begin manufacturing, improve on those technologies, and, finally, patent them.[95] When firms are unwilling to license their technology and China imposes barriers to trade, however, the reality of Chinese business practices may compel foreign firms to form joint ventures. In the case of waste heat recovery technologies for steel and cement plants, Japanese companies originally exported the necessary components, but Chinese manufacturers started producing "imitated or similar products" with much lower labor costs. In order to compete effectively, the Japanese companies began to establish joint ventures.[96]

The Indian economy is far more open than the Chinese economy. Yet its industrial structure also leads to important limitations to the flow of technology. The success of India's software and business process firms is now well known. Exports in these sectors rose from about $10 billion in 2000 to $72 billion in 2009; KPMG, the global tax, audit, and advisory firm, predicts that the domestic and exports markets will reach $285 billion by 2020. Yet these sectors are in many ways outliers within the broader landscape of Indian technology.

Historically in India, the percentage of total exports made up by high-tech goods (a little more than 5 percent in 2007) has been less than in Brazil (close to 15 percent) and much less than in China (close to 30 percent, though that figure is inflated by the presence of foreign high-tech components in products that are assembled in China). Still,

Indian manufacturing has been growing at a healthy rate, the global economic recession of 2008–2009 excepted.[97] Merchandise exports reached $182.6 billion in 2008–2009, up from $63.8 billion in March 2004. Manufacturing as a share of GDP, however, remains at about 17 percent, below the 25 to 30 percent medium-term goal set by the government—and well below the 33 percent in China. Approximately seven million people work in manufacturing in India, compared with one hundred million in China, and few new jobs have resulted from the sector's expansion. In fact, India's "organized sector" has been shrinking as manufacturing has required more technology and capital.[98]

The largest Indian business groups—Tata, Mahindra, and Reliance—are all involved in renewable energy and energy efficiency, either directly or through subsidiaries. These big firms have deep pockets and bring a recognized brand to what still is not a mainstream product, allowing for much needed experimentation and patience. At the same time, these firms have downsides. Large firms are inevitably less nimble and have longer decision-making cycles than small start-ups. In India, the large conglomerates tend to be strongly biased toward developing technology internally over acquiring technology from outside the company. That said, small players are becoming more prominent in India's clean energy industry. They are supported by a growing group of venture capitalists and private equity investors, many based in the United States, who provide not only capital but also much-needed connections among firms.

As in the Chinese case, there are still significant distortions in the Indian capital markets, although the private sector and equity markets are more developed there than in China. The government continues to run large deficits to fund rural development plans. Indians save about 30 percent of household income, but only about half of this is invested in bank deposits. The equity markets have grown rapidly, and unlike in China, where state-owned enterprises dominate the listings, private companies make up 70 percent of equity market capital. According to McKinsey, public sector banks make up 75 percent of the banking system, and state-owned companies and government-directed sectors receive priority in bank lending. Private companies receive a little over 40 percent of commercial credit.[99]

Foreign venture capitalists have become dramatically more interested in India recently. Venture capital firms invested $475 million over ninety-two deals in India during 2009, up from 2008 but a significant

drop from $928 million in eighty deals during 2007.[100] Close to 40 percent of venture capital investment in 2009 went to the clean technology sector, with more than half of that going to energy generation and biofuels in particular, according to the Cleantech Group.[101] Still, it is not clear that venture capital will dramatically transform innovation in India's clean energy sector. For most firms, the opportunities available in low-risk, high-profit areas such as services, telecom, or retail are much more attractive than science-based innovation in highly uncertain markets.[102]

Most Indian firms do not appear to be biased against foreign technology. As a manager at one of the large business houses put it, "Frankly, I don't care where the technology came from as long as the customer wants and it is commercially viable." Indeed, all the major Indian clean energy efforts to date have depended heavily on foreign technology. The wind industry, for example, has its roots in a Danish aid project that sent wind turbines to India to help with drilling wells, and much of the most technologically sophisticated equipment is still imported. One interviewee estimated that 85 percent of the value chain for solar PV is imported. To the extent that Indian firms are biased against foreign technology, the attitude tends to be concentrated in state-owned enterprises, or public sector units, which contributed 20.5 percent of GDP and 24.2 percent of gross domestic capital formation in 2007–2008.[103]

Openness to foreign technology is necessary because Indian firms have not traditionally produced their own. Unlike in China, where 60 percent of all R&D takes place in industry, close to 80 percent of all R&D in India is conducted by the government. Of that government spending, 60 percent flows through national security programs—including the Department of Atomic Energy, the Indian Space Research Organization, the Council for Scientific and Industrial Research, and the Defense Research and Development Organization—and so has little immediate commercial use.

In addition, because of the large gap between what industry and academia are interested in, there has been little interaction between the two—a growing concern for policymakers. The National Research Development Corporation, a department under the Department of Science and Technology, licenses technologies developed in university and government-run labs and invests in new ventures. The National Science and Technology Entrepreneurship Development Board, whose mission is to generate entrepreneurship among scientists and engineers, has

established industry-university cells, science and technology entrepreneur parks, and technology business incubators.[104]

In the corporate sector in India, R&D spending is minuscule. The software giants Wipro and TCS, for example, spend only around 0.2 percent of their sales on R&D, and Infosys spends a little over 1 percent.[105] Multinational R&D centers are the exception. Nearly 150 of the Fortune 500 companies have R&D facilities in India; in 2008, there were 594 multinational R&D centers in India, employing 146,760 workers.[106] The Danish wind power company Vestas, for example, came to India to be close to abundant engineering talent and to Chennai in particular to be near related industrial activity, such as automobile part factories and information technology centers. The company's India operation is now its largest technology center outside of Denmark, and it is designing and developing new components and products, rather than focusing on adapting Vestas products to the Indian market. Most of this R&D, however, is captured by the multinational corporations and has little impact on the technological capacity of Indian firms.

Indian companies have been flexible in their approaches toward acquiring foreign technology. Tata Power and BP Solar, for example, established a joint venture in 1989 (called Tata-BP Solar) that develops solar PV and thermal products and systems at its manufacturing facilities in Bangalore. This joint venture has spread market understanding and critical knowledge possessed by workers—at one of the big business houses, one of the principal managers behind the solar initiative previously worked for Tata-BP Solar.

Indian firms have also successfully acquired technology through the purchase of foreign firms. There are, however, cautionary tales. The wind company Suzlon, for example, is often cited as a major example of Indian success at buying foreign technology. Yet after acquiring REpower Systems AG, a German turbine manufacturer, Suzlon faced major problems. It had difficulty integrating management and business operations, retaining essential personnel, and dealing with exposure to the 2008–2009 recession due to the increased leverage needed to finance the deal. (Suzlon acquired the company with the intention of gaining a product for markets around the world.) As a result, as of early 2010, the company had gone from being a darling of the clean energy world to being on shaky ground.

Brazil's private sector boasts many companies that have proven capable in obtaining and adapting advanced technologies. For decades,

Brazil has attracted large multinational corporations, either through the creation of their own stand-alone subsidiaries or in joint ventures with local firms, particularly in economic sectors with high value-added technologies. Other companies, such as the domestically owned Embraer, have developed their own technologies (in association with Brazil's military research establishment) that now compete on the world stage. Yet there are structural limitations to Brazil's ability to create and absorb technology.

Only recently did Brazil's longer-term financial markets begin to develop. Local banks are now starting to build active commercial loan portfolios, and some recent regulatory changes in banking should help expand this market. As the Brazilian economy has grown, foreign interest in the country has exploded—from banks as well as private equity groups and hedge funds. This, too, is adding liquidity to the market. And in the last decade, Brazil's stock exchange, the BOVESPA, has expanded to become the ninth largest exchange in the world, providing a new avenue for funding of new projects, including the acquisition of technology.

Within these various types of financing, many investors are showing a keen interest in green investment and setting up new funds. Local and foreign banks, including the Santander Group, Mitsubishi UFJ, Bradesco, Itau-Unibanco, and Banco do Brasil, have set aside funds for "clean development mechanism" projects in particular. In 2009, Brazil came in second, after the United States, in leading venture capital and private equity financing for renewable energy and energy efficiency.[107] BNDES, too, has played an important role, by funding these initiatives and helping develop the relationships necessary to support long-term development. For instance, BNDES is helping large Brazilian companies such as Vale—a longtime bank client and now the world's leading iron ore producer—with financing for a start-up company to create off-grid sustainable energy sources for its Brazilian operations.

But the markets for commercial loans, private equity, and public equity are all still quite new, and it is hard to know if they will foment the creation and transfer of technology on a large scale. Access to this capital is still generally limited to large, well-established national and international companies. While more accessible than ever before, the BNDES and the private financial markets still leave many small and medium-sized companies without financing. This, in turn, makes it difficult to acquire or commercialize new technologies.

There are other challenges for the wider array of Brazil's commercial enterprises. Smaller and lesser known companies have a harder time defending any intellectual property rights they may possess and sometimes have limited interest in defending those of others, making technology transfer to them less attractive for multinational corporations. Nevertheless, as recent joint ventures and acquisitions in Brazil attest, large international corporations interested in Brazil are bringing information and know-how into the country.

Brazil has also found it difficult to commercialize inventions. Although Brazil is a recognized leader in clean energy sources such as biofuels, it has made less progress translating these sources into easily adoptable products. In part, this results from the disconnect between academia and the private sector, despite the fact that universities play an outsized role in technology innovation. The Brazilian government's long history of funding research has caused Brazil to have a patent ownership structure that is quite different from those elsewhere. Whereas in developed countries less than 3 percent of patents are owned by universities, in Brazil academic institutions maintain 27 percent of all registered patents, which reflects the low level of industry R&D.[108] According to the latest study by the National Institute for Industrial Property, the University of Campinas ranks third in the nation in terms of patent ownership, ahead of world-renowned companies such as the oil producer Petrobras, the appliance maker Multibras, and the aircraft manufacturer Embraer. Seventy percent of researchers, meanwhile, work in universities, with only 10 percent in industry and 15 percent in the government, in contrast to the United States, where 80 percent of researchers are in industry.[109]

Although this divide is not necessarily a problem for initial innovation, it hampers the commercialization of new technologies and ideas, meaning that they will take much more time to be deployed. There have been some efforts in the clean technology sector to overcome this problem, particularly in the biofuels industry. The Center for Sugarcane Technology (CTC), Brazil's largest sugarcane technology center, has created a cooperative model with sugar growers and mills to distribute its technology to the private sector. The center has also brokered agreements with leading multinational corporations—including BASF, Novozymes, and Bayer CropScience—to further innovation and the commercialization of their products.

Brazil has had extensive experience absorbing foreign technology. Traditionally, technology has come to Brazil through joint ventures

between domestic and foreign companies, often backed by the state with incentives or direct investment. This trilateral arrangement has helped develop Brazil's aeronautics, electronics, and chemicals industries, among others. Direct foreign investment by multinational corporations—in areas as diverse as automobiles, food processing, and drug manufacturing—has also been important.

In clean energy technology, too, joint ventures between local and foreign companies remain a chief means for technology transfer. U.S. companies have viewed the Brazilian market favorably and are becoming important players in the local market. For example, in the market for ethanol and other biofuels, the agricultural leader Monsanto began collaborating in 2006 with local companies CanaVialis and Alellyx to develop and commercialize genetic engineering and technology for sugarcane. In 2008, it acquired the two Brazilian firms, cementing its interest in becoming a worldwide leader in sugar biotechnology.[110] ADM is also active through a joint venture with local investors, while the oil giant Royal Dutch Shell recently agreed to a $12 billion deal with COSAN, a Brazilian company, to form one of the world's largest ethanol producers.[111] Several other multinational corporations have joined with local companies to exploit domestic and international opportunities in the sector, forming, for instance, the wind companies Ventos do Sul and Desenvix.[112]

International companies also come on their own, bringing their technology and know-how to Brazil's growing domestic market. In wind energy, for example, Brazil now boasts international powerhouses such as Germany's Siemens. In addition, GE recently announced that it will build a state-of-the-art R&D center in Brazil to focus on energy and infrastructure. Encompassing some three hundred engineers, it will be the second largest center outside of the United States in the world. GE has promised to work with local universities to revamp curricula and provide the training necessary to staff its future operations, steps that will enhance Brazil's human capital.

TECHNOLOGY SALES

Spreading technologies to the major emerging economies can ultimately increase those countries' exports of the same technologies. This is a double-edged sword for U.S. firms and workers, and for the United

States as a whole. Technology exports by the major emerging economies into the U.S economy can provide the United States with lower-cost options for addressing clean energy problems or foundations that U.S. firms and inventors can build upon. But they can also compete with U.S. firms, potentially lowering profits from clean energy technologies. The potential for emerging economies to export technologies should thus be an important factor in determining the United States' international strategy for low-carbon technology.

China believes its clean energy industry can play a leading role in the global marketplace. Vice-Premier Li Keqiang has called the energy-saving industry a "strategic new industry" with the potential to achieve an output worth four trillion yuan (almost $600 billion) between 2010 and 2015.[113] China is already the largest producer of solar PV cells and modules, of which it exports over 90 percent, and the second largest producer of wind turbines, compact fluorescent lightbulbs, and light-emitting diode (LED) lights.[114] The Ministry of Commerce is aggressively promoting Chinese clean technology exports through its "all-in-one service," which includes providing not only equipment but also expertise and services.[115] China has also promised to develop one thousand clean technology projects throughout Africa. The Chinese government will extend loans to developing countries, which will be used to pay for Chinese-made equipment, workers, and technologies. This strategy has already proved successful in the hydropower industry; of the twenty-four largest hydropower plants under construction worldwide, Chinese firms are now building nineteen of them.[116] The state-owned hydropower firms Sinohydro and Gezhouba have a near monopoly throughout the developing world: Sinohydro has plants under way in Cambodia, Laos, and Myanmar, while Gezhouba is signing contracts in Nigeria, Ethiopia, Equatorial Guinea, and Algeria. But China is especially keen to expand its presence in the United States and Europe. Chinese clean energy experts believe that the quality these advanced markets demand will help improve the quality of manufacturing in China.[117] These same experts, however, are also aware that the current state of Chinese quality control often excludes Chinese companies from those markets.

Indian firms are confident in their ability to compete with and bring technology to other emerging economies, but they are less focused on developed-country markets. The experience that Indian companies have with managing solar in isolated rural areas, for example, is expected to

give them a leg up in Africa. Similarly, several years of building hybrid and electric cars and trucks will give Indian firms a significant competitive advantage in markets that lack adequate highways. These "bottom of the pyramid" business processes are also what Indian officials talk about as their contribution to the proposed climate innovation centers. That said, Indians are also interested in supplying developed-country markets, building on the success of Suzlon in wind and Tata in automobiles. People speak of leveraging Indian strength in information technology, systems engineering, and mechanical engineering to produce globally viable technologies in smart grids, green buildings, and concentrated solar thermal power.

As the largest world exporter of biofuels, Brazil is already a leader in the clean energy trade. A 2009 study by the World Wildlife Fund (which, it should be noted, was restricted to renewable energy) ranked Brazil second in the world in terms of clean energy technology product sales weighted by GDP and sixth overall in absolute terms.[118] The country has aspirations to substantially increase its exports of low-carbon technology—such as genetically engineered sugarcane plants, high-efficiency milling technology, and technology for flex-fuel cars—primarily to other developing countries but also, if possible, to developed countries. With all of these technologies, though, Brazil has made exporting internationally a secondary priority to producing for domestic markets. Most of the push for exports comes from the private sector, which, with the most competitive cost structure for biofuels in the world, sees sizable market opportunities abroad. But it also comes from the Brazilian government. The foreign ministry is working diligently to promote Brazilian biofuel technology as a way to solidify relationships with developing countries, signing over sixty memorandums of understanding toward bilateral technical cooperation in the area of sugarcane production alone. Actual sales of such technology, though more limited in scope than the memorandums of understanding, have occurred in Jamaica, Mozambique, Sudan, the Democratic Republic of the Congo, Angola, and Uganda.

U.S. Policy Analysis and Recommendations

There are two natural extremes that the United States' international technology strategy could take. The first strategy would see the country prioritizing climate change over traditional economic interests. Washington would help developing countries indigenize low-carbon technologies without worrying about how those policies affected U.S. technology producers. Such a strategy would try to exploit the fact that indigenization of low-carbon technologies can, in many cases, promote the greater use of those technologies, and hence reduce carbon emissions in the major emerging economies.Yet such a strategy would likely run into three critical difficulties. It would almost certainly fail to attract cooperation from U.S. firms engaged in low-carbon technology development and production—which would be necessary for the strategy to have any chance of success.[119] Moreover, if such a strategy reduced U.S. firms' incentives to innovate, it could undermine the foundation on which it was based. A strategy focused narrowly on pushing technology transfer through U.S. policy would also fail to address the obstacles to the flow of technology that are imposed by the barriers to trade, investment, and intellectual property protection in developing countries themselves.

At the other extreme, the United States could decisively prioritize traditional economic interests over climate change. It would press the major emerging economies to remove barriers to trade and investment and strengthen their protection of intellectual property rights.[120] This strategy would seek to remedy the significant damage these barriers often inflict on the ability of U.S. firms to maximize economic returns. It would also address those firms' concerns about the potential for government-driven technology transfer, such as through compulsory licensing, to hurt their bottom lines.

Yet such a strategy would encounter major problems, too. The emerging economies might see little reason to play along and, through control over their own trade, investment, and IPR policies, sink the strategy. Moreover, such a strategy would sacrifice environmental goals;

the spread of low-carbon technology is likely to be too slow without a policy push, particularly because of structural weaknesses in emerging economies' innovation systems. Killing all barriers to trade and investment, and thus weakening domestic industries in the major emerging economies, is also likely to sap political support for emissions-cutting efforts in those countries.

Because neither extreme is optimal, the United States should combine these two approaches. It should encourage openness to commercial low-carbon technology flows on the part of the major emerging economies while actively promoting the spread of technology itself. Enlarging markets for low-carbon technologies by removing barriers to trade, investment, and the secure spread of ideas would address U.S. firms' and workers' commercial concerns about government involvement in technology flows. Actively promoting technology transfer, meanwhile, would reassure developing countries that their own firms would also benefit from moves to grow and open their low-carbon technology markets. At least as important, wise government intervention would compensate for market failures—most notably underinvestment in risky technologies—that retard development and diffusion of low-carbon technology not only within but also across borders. As far as the environment goes, these two elements would also reinforce each other: commercial openness and active promotion of technology transfer would both accelerate the innovation, diffusion, and deployment of low-carbon technologies.

If, however, a particular country were to adopt a persistently closed approach to commercial technology flows, the United States would be unwise to blindly persist in actively promoting technology transfer to that country, too; doing so would reduce incentives for the country to open up in the first place. It would also undermine essential support of U.S. firms and workers for the overall strategy. The United States should thus respond to new limits on commercial technology transfer by prudently reducing its own governmental support for technology cooperation with the offending country.

INVEST IN INNOVATION AT HOME

Before the United States can pursue a serious international technology strategy, though, it must strengthen its own system for low-carbon

innovation. It cannot depend on others to develop the low-carbon technologies of the future. There is substantial innovative activity across the world, including in the major emerging economies, but those efforts have significant shortcomings. Stronger U.S. government support for innovation in low-carbon technology would strengthen the platform on which the United States can engage in low-carbon technology efforts abroad.

This support should have two basic elements. First, the United States should create large domestic markets for low-carbon products and services. Second, it should support innovation directly by helping pay for low-carbon research, development, and demonstration projects, as well as by adopting policies that encourage investors to finance companies through the period in which a product has been invented but not yet commercialized, which is known as the valley of death.

Almost all who accept that climate change is a serious problem agree that the U.S. government must create incentives for the widespread adoption of clean energy technology. Growing markets incentivize innovation by giving firms and inventors greater returns on their low-carbon investments. There is, of course, disagreement regarding the most appropriate form such incentives should take, with some calling for carbon pricing, others preferring broad-based regulation, and still others pushing for specific mandates. Resolving that conflict is beyond the scope of this study. Yet through one mechanism or another, the United States must encourage widespread domestic adoption of low-carbon technologies.

Support on the supply side is required, too. As it stands now, private firms and researchers will collectively invest less than is socially optimal in R&D, since no one firm or inventor can reap the full benefits of an investment. This shortfall extends to later stages of the innovation process, including demonstration of many new technologies and commercial piloting of many risky technologies. These problems are particularly acute in capital-intensive sectors and in sectors where commercialization is slow, since neither type of area is well matched by traditional venture capital or private equity financing models. Alas, clean energy exhibits both characteristics.

Government support can help fill those gaps. Several authors and groups of leaders have recommended, persuasively, that the U.S. government increase its investment in energy technology innovation by two to three times, to $10 billion to $15 billion annually. This figure

is both prudent and manageable (and is far less than what the United States spends on many other major challenges). Money could be spent through a mix of direct public funding of innovative activities, public-private partnerships, and public support for privately financed and privately executed innovation.[121] As always, there is a real risk that government dollars could be poorly allocated. But that danger is outweighed by the risk that, absent government action, the United States will not deliver the innovations necessary to eventually de-carbonize the economy. Moreover, the U.S. government can reduce its risks by insulating the allocation of funds as much as possible from the political process, and by avoiding putting too much emphasis on any one particular technology or firm.

The U.S. government should stop short of mirroring the major emerging economies by helping finance the manufacture of mature low-carbon technologies. (Short-term economic stimulus spending, motivated primarily by broader economic concerns rather than by competitiveness goals, is a possible exception.) As many have pointed out, innovation and manufacturing are tightly linked. New ideas often come from those who are most familiar with and are engaged in the production process. Locating manufacturing and R&D facilities near each other would likely create positive externalities that could have significant payoffs for a particular region.[122] But these initiatives, to the extent that they are wise, should come from state and local authorities since they are better positioned than the federal government to assess, design, and implement them. They should also be designed to comply with U.S. obligations under the WTO. Moreover, the more the U.S. government gets involved in promoting clean energy manufacturing, the greater public pressure for counterproductive protectionist policies is likely to be.

That said, it is almost inevitable that a U.S. government more involved in low-carbon innovation would become more involved in decisions about the flow of technology that have traditionally been the sole province of private actors. This would also spill over into trade politics, since any government that promotes the development of low-carbon technology on the grounds of competitiveness may find itself under greater pressure to actively shape the playing field for technology flows, too. These complications are outweighed, however, by the overwhelming need for the U.S. government to help promote innovation in low-carbon technology.

ENCOURAGE AN OPEN INTERNATIONAL SYSTEM FOR LOW-CARBON INNOVATION AND DIFFUSION

Since openness tends to accelerate innovation in low-carbon technology, promote the diffusion of that technology, and reduce costs for all involved, the United States should actively promote openness at all phases of the innovation process. But it should also be sensitive to the fact that some limited protections may be necessary to build political support for policies that create demand for low-carbon technology. Moreover, it should be aware that some policies in this area that are good for the United States may not be good for some individual companies, which will oppose them. When pursuing openness, the United States should concentrate on three areas: ideas, investment, and trade. In each category, it should reinforce its efforts by ensuring that its own markets and innovation system remain open, too.

IDEAS

An open environment for the flow of ideas is one in which ownership of ideas is protected and access to them is maximized. U.S. policy in this area should seek to strengthen the implementation of intellectual property laws in the major emerging economies while guarding against abuses by firms (both U.S. and foreign) with dangerously large market power. Any adjustments to intellectual property rules (which we discuss in the next section) should be made deliberately and cooperatively, rather than through the weak enforcement of accepted laws.

The role of IPR in promoting or inhibiting international low-carbon technology transfer is often overstated. Still, IPR policy is important in several situations. The United States should continue to press China to strengthen its protection of IPR and, perhaps more important, to avoid indigenous innovation policies that deliberately aim to force the transfer of intellectual property. While poor IPR protection has not prevented many companies from bringing low-carbon technology to China, it undoubtedly slows them down and encourages them to keep some of their best technology at home. Meanwhile, there is little risk that Chinese efforts to promote the deployment of low-carbon technology would backslide if the United States scored a victory on IPR protection there.

Compared with those in China, IPR rules in India and Brazil are much better enforced, and that enforcement is improving. The United States should simply encourage this trend by emphasizing its importance to a strong and productive economic relationship.

INVESTMENT

Cross-border investment, whether through joint ventures or foreign direct investment, facilitates technology transfer. India and Brazil have maintained relatively open approaches to foreign investment in their low-carbon technology sectors. Foreign direct investment has been a particularly prominent mode of low-carbon technology transfer to Brazil, whereas joint ventures with majority foreign ownership have dominated in India. China, by contrast, has adopted a much more closed approach to foreign investment, hoping that its large market will still lure companies. For this reason, most foreign low-carbon investment in China has come through joint ventures with majority Chinese ownership, which can deter technology transfer and prevent foreign technology owners from capitalizing on their innovations.

The U.S. strategy for investment should be similar to that on the IPR front. The United States should encourage India and Brazil to maintain their largely open approaches. But there is still room for progress around the edges. The United States should press back against Brazil's incipient efforts to use BNDES and Petrobras to crowd foreign firms out of the Brazilian ethanol business. In India, it should encourage greater openness to foreign participation in government-backed technology demonstration efforts, in contrast with the current Indian approach to IGCC, which excludes foreign technology.

The Chinese case is much more challenging and complex. U.S. firms are increasingly wary of investing in China because the Chinese government's procurement policies, along with other discriminatory policies, place them at a disadvantage. Washington should press Beijing to relax its restrictions by complaining early about problematic policies and by coordinating its efforts with other aggrieved countries. It should also withhold some of its support for efforts that actively promote the spread of technology to China if Chinese investment and trade barriers are so high that U.S. low-carbon innovators do not stand to benefit from a deal. That said, the United States should be realistic about the limited amount of leverage that these tactics will yield.

TRADE

All three major emerging economies impose significant barriers to trade in low-carbon technologies, which, in turn, inhibit technology flows and closes off commercial opportunities for U.S. firms. The United States must push back. It should especially target barriers that not only hurt foreign firms but also severely retard the adoption of low-carbon technology. (Indian restrictions on imports of silicon wafers for its National Solar Mission, if such restrictions were to be imposed, would be an example of such barriers.) Washington should be willing, however, to tolerate some trade barriers that are essential to building political support for government measures that promote emissions-cutting technology. (India's restrictions on imports of complete solar modules, for example, might have this effect.)

China, once again, should be the focus of the greatest attention. The United States has been largely unsuccessful in resisting Chinese trade barriers. A strategy to change this would, once again, see the United States join forces with other countries hurt by Chinese practices, and, as a last resort, tie U.S. openness to Chinese products to China's own market access policies. Fortunately, there is little risk that getting China to remove barriers to trade would lead it to abandon efforts to deploy low-carbon technologies.

India is a more mixed case. Its trade barriers are generally more subtle and less damaging to technology diffusion. One emerging exception involves the National Solar Mission. The United States should push back against rules that exclude foreign cell and module manufacturers for the first two years of the mission. Reportedly, it has done just that. Indeed the Indian government is apparently considering adjusting the rules after complaints from the United States and others. (China and Taiwan are more likely to be damaged by those rules than is the United States.) This suggests that early intervention and continued dialogue could help avoid possible problems.

Of the three countries, Brazil has the least problematic barriers to trade. Its barriers largely apply to products, such as low-capacity (and relatively low-tech) wind turbines, that the United States has little interest in selling anyhow. (Again, China is probably the foreign producer most affected.) Meanwhile, Brazil recently removed barriers for products like high-capacity wind turbines and in biofuels that are of greater interest to the United States. The United States should encourage the

Brazilian government to keep making progress. Implicitly, however, Brazil has raised some barriers to trade by providing preferential financing for low-carbon technology firms that manufacture domestically. In the broad scheme of possible protectionist measures, this is far less egregious than the alternatives. The United States should tolerate this policy unless it is used to build an unreasonable export advantage (rather than to simply help satisfy domestic markets).

U.S. policy should also attempt to harmonize standards for low-carbon technologies with other major producing countries. Common standards in areas like charging electric vehicles or assessing biofuels' emissions can allow technology developed for one market to be easily deployed in another. Harmonized standards not only speed up deployment but also accelerate innovation, since inventors in both markets can build on each others' developments. Coordination, whether through bilateral cooperation or intergovernmental organizations, can also help preempt the sort of unilateral standard setting that China has used to block foreign products and technologies from its markets (most notoriously in the case of WAPI, China's competing standard to WiFi). The U.S. government is currently working with Brazil on biofuels standards and with China on standards for electric vehicles. It should continue these efforts and seek out other opportunities to develop common standards where appropriate.

To be certain, though, coordinating standards can have downsides. By narrowing the range of viable technologies, there is a danger that a standard may deliver considerably more market power to a single innovator than would have existed otherwise. One firm may hold a patent that is necessary to satisfy a fixed standard. This introduces a barrier to technology transfer and diffusion where one would not have been. To avoid this problem, firms involved in standards setting processes should agree in advance to limit the royalties that they can extract in such situations.[123]

U.S. MARKETS

How and whether the United States welcomes foreign imports and investment in low-carbon technologies will both affect its leverage over other countries' policies and affect technology flows directly. The United States should largely maintain an open approach but protect itself from unfair competition.

NUCLEAR POWER

Governments have historically played outsized roles in technology transfer related to nuclear power because of the national security concerns associated with the spread of nuclear energy technology. The United States and China did not sign a nuclear cooperation agreement, required for the commercial transfer of U.S. nuclear technology, until 1985, and that agreement was not implemented until 1998, when the United States certified that China was no longer involved in nuclear proliferation. Brazil signed a nuclear cooperation agreement with the United States in 1955, but the two countries have repeatedly come into conflict over Brazil's pursuit of uranium enrichment technology. The U.S.-India relationship has been the worst: the United States stopped nuclear commerce with India following its nuclear detonation in 1974, and for three decades, the situation remained unchanged. The 2005 U.S.-India nuclear deal promised to reopen commerce between the two sides, but five years later, the final hurdles to implementation have just been cleared.

The U.S. government will continue to play an unusually active role in nuclear technology transfer in the future. The three major emerging economies may, however, see fewer effects than others. U.S. policy is aimed primarily at preventing the spread of sensitive nuclear fuel cycle technologies—uranium enrichment and reprorcessing—to states that do not already have them. All three countries, however, are already at varying advanced stages in their enrichment programs. However, if U.S. firms commercialize new enrichment technologies, the U.S. government may move to block their spread, including to others that already have enrichment technology. (GE, for example, is reportedly trying to commercialize laser isotope enrichement, long a major concern of nonproliferation analysts.) The United States, meanwhile, does not currently pursue reprocessing, though that might change in the future. Moreover, while enrichment and reprocessing can make states feel more independent, they have limited impact on the economics of nuclear energy, which are driven mainly by plant rather than fuel costs.

India is likely to present the greatest future complications. The new environment for civil nuclear commerce established through the 2005 nuclear deal is still embryonic. The political difficulty of implementing the agreement in both the United States and India has led to moves on both sides that may make nuclear commerce more difficult. India, in particular, has recently passed laws that extend liability for nuclear accidents in unprecedented ways. Analysts project that this will have the effect of biasing the Indian market against private firms (including U.S. firms) and toward state owned enterprises (such as those in Russia).

As the United States crafts future policy, it will have to keep nonproliferation as a high priority while also accommodating climate concerns. If history is any indication, though, commercial forces will ultimately prevail. An enlightened strategy will attempt to shape the environment for commercial transfer of nuclear technology rather than trying to block such transfer outright.

The United States does not currently impose significant restrictions on foreign investment in clean technology. Politicians, unions, and lobby groups have, however, called for restrictions on foreign investment in companies that receive economic stimulus funds. Similarly, although the United States does not impose significant barriers to imports of low-carbon products, some have called for such limits for projects supported by stimulus funds. If future support for clean technology manufacturing is also supported by U.S. government funds, or by even government regulation, there may be renewed calls for similar restrictions.

The United States should welcome foreign goods and capital in its clean energy projects when their presence arises from a genuine comparative advantage, as will often be the case. If, however, foreign firms are playing an outsized role thanks to unfair industrial policies, it may be prudent to restrict their participation in projects funded by U.S. taxpayers. (Compliance with WTO rules is one useful benchmark against whether to judge whether countries' policies are fair.) Such an approach is unlikely to cause problems with India or Brazil, so long as their policies do not change considerably.[124] China, however, presents a different case. Chinese firms benefit from the extremely low cost of capital and from government subsidies that implicitly aid exports, as well as from

an undervalued currency. The United States should consider using the remedies available to it under the WTO to block unfair exports from the U.S. market. But it should prioritize responses that do not further inhibit low-carbon innovation and technology diffusion; be careful not to sweep up others, such as Europe and Japan, in overly broad restrictions; and avoid setting unreasonable protectionist precedents or provoking unacceptable retaliation.

The United States should also clarify its stance regarding the purchase of U.S. clean technology companies by foreign firms. As the case studies in this report show, this is often a preferred route for technology transfer. Yet some fear that if low-carbon technology becomes seen as a critical national asset, the United States might refuse to allow the sale of major firms, just as it did in 2006, when it effectively blocked the sale of the oil company Unocal to China National Offshore Oil Corporation (CNOOC), citing national security concerns. This fear is most acute for China, which is both an economic and a military competitor, and less important for other countries. The United States should reassure the major emerging economies, including China, that it will not block the sale of low-carbon technologies to them unless militarily sensitive technologies are associated with the sale or the purchase appears to be part of an effort to corner a critical market.

Finally, the United States should take care to ensure that its own national security export controls do no unnecessarily slow down technology diffusion. These have proved problematic in the past with nuclear technology and with advanced materials for IGCC technology. Advanced materials, which often have alternative military uses, may become increasingly important in low-carbon innovations. There is no simple rule for addressing this tension; national security concerns will often legitimately prevail. But in making decisions about national security export controls, the United States should be careful that promoting the spread of low-carbon technology is considered a high-level objective.[125]

ACTIVELY PROMOTE TECHNOLOGY TRANSFER

Neither openness nor greater investment in innovation alone is enough. Technology has to be pushed out into emerging economies throughout the innovation process—from R&D, through demonstration and

commercialization, to diffusion and deployment. Just as the existence of market failures means that governments sometimes need to step in to promote innovation within their own borders, governments will occasionally need to help promote innovative activities that span multiple countries too. The United States should, however, withhold certain elements of technology transfer cooperation when dealing with countries that do not adopt open and cooperative approaches themselves. It will also need to guard against unwisely undermining U.S. competitiveness.

COOPERATE INTERNATIONALLY ON RESEARCH AND DEVELOPMENT

The United States should support joint and coordinated programs for low-carbon R&D with China, India, and Brazil. Cooperation on R&D helps minimize the costs to all participants in areas where the benefits of any successful R&D will accrue to each of them. It can give each participant greater insight into the others' markets, and it can strengthen technological confidence on the part of emerging market governments, which may make them more likely to pursue low-carbon economic development. Indeed, our research has shown that early-stage R&D is generally the area in which those countries are weakest.

The United States should pursue joint R&D and promote joint R&D in industry, even with those countries whose low-carbon innovation systems and product markets are less open than it would prefer. At this early stage, R&D is often well removed from commercial application—a market that is relatively closed today could be considerably more open by the time firms are able to commercialize any inventions resulting from joint R&D. Our interviews with policymakers in China, India, and Brazil also suggest that withholding cooperation on R&D would provide the United States little, if any, leverage in making them more open to U.S. technology.

The United States has already taken some steps to strengthen joint R&D. It is establishing a U.S.-China Clean Energy Research Center and a U.S.-India Joint Research Center. And it has struck cooperative R&D agreements with Brazil, though it does not have dedicated institutions for cooperative research. Researchers in the U.S. government also often cooperate with scientists in the major emerging economies through individual projects.

The United States should spend more on collaborative R&D and establish a third joint center with Brazil to focus on biofuels and

agriculture. It should increase its efforts to draw private sector R&D participants, too, into these transnational efforts. It should also provide flexible funding to U.S. government researchers (and to academic researchers supported by the U.S. government) that lets them cooperate with counterparts in the major emerging economies on an ad hoc basis, rather than only in the context of large, dedicated projects. This would allow them to take advantage of unanticipated opportunities.

The United States should also beware that calls for equal funding of joint R&D, which often come from the U.S Congress and are often justifiable, can be a barrier to cooperation. This is particularly true in the case of India, which has far less money than Brazil or China. Much cooperative R&D is more than worth the U.S. investment even when the United States funds a disproportionate share of the work. It should be open to doing so more often.

The U.S. government's own R&D activities should also be designed with an eye toward applications in the major emerging economies—an approach that does not require cooperation on actual R&D. U.S. government researchers should spend part of their time investigating technology that may not necessarily have applications in the United States. Scientists should craft their work in ways that maximize the range of possible applications. One policymaker in India, for example, suggested that U.S. R&D for superefficient appliances focus on individual components, rather than just on complete systems, so that these could be integrated in different ways in different countries.

IMPROVE INTELLECTUAL PROPERTY RIGHTS SYSTEMS

The cost of patents is currently a small part of the cost of most low-carbon technologies.[126] This is why strategies aimed at addressing the cost of patents—often a focus in discussions about climate change—would not decisively tilt the economic playing field in favor of low-carbon options. It would, however, reduce the incentives for inventors to cooperate in commercialization, since they would not see the same market returns. (To the extent that low-carbon innovation is spurred by government, though, incentives to invest in innovation will remain.) The United States should not pursue such policies.

There are, however, two efforts on the IPR front that the United States should pursue. Both of them would address companies' willingness to license technology, rather than the cost of patents. The first is to provide IPR insurance for small and medium-sized enterprises.[127]

(IPR insurance would be designed to pay out if a company's IPR was misappropriated.) Companies of this size, which generate a large fraction of inventions in the United States, can have large portions of their value tied up in their intellectual property, and weak protections for intellectual property would threaten their viability and deter them from being active in the major emerging economies. Conversely, in the major emerging economies, smaller firms have greater difficulty engaging in commercial technology transfer than their larger counterparts: larger firms have more to risk (in terms of value and reputation) by violating IPR rules; smaller firms have a harder time establishing credibility and hence in attracting partners for technology transfer. Yet in countries with well-functioning innovation systems, small firms, which can be nimble and risk tolerant, are often at the forefront of the spread of technology. To strengthen commercial technology transfer among smaller firms, the United States should support intellectual property insurance for U.S. innovators that are attempting to commercialize their inventions in the major emerging economies. But it should do this only for countries that have not adopted hostile approaches to IPR. China, namely, should not be a candidate for IPR insurance unless it pares back its current indigenous innovation strategy.

The second effort involves compulsory licensing. The major emerging economies already have some recourse to compulsory licensing under special circumstances through the WTO TRIPS agreement (notably in cases where they have tried but failed to obtain licenses on commercial terms). There may be isolated occasions in which the U.S. government should accept the issuing for compulsory licenses for low-carbon technologies by the major emerging economies. Larger firms that make their money by manufacturing products can use control over intellectual property to monopolize markets, either by refusing to license their intellectual property or by acquiring exclusive licenses from inventors. This sort of profit-seeking behavior is often reasonable, but it can also prevent the timely diffusion of needed low-carbon technologies. In such situations, government steps to force licensing may be justified.

But the United States should be extremely careful about compulsory licensing. If the United States entered an international agreement that allowed other governments to grant compulsory licenses for U.S.-owned technologies without regard for the basic requirements established through TRIPS, major emerging economies could abuse

the strategy to appropriate intellectual property as part of an aggressive policy. More fundamentally, forcing the owner of a technology to license its intellectual property will usually fail to promote technology transfer, since the owner will likely refuse to also transfer the complementary knowledge required to make use of it. In such cases, there is no point in compulsory licensing. At a minimum, any steps to force licensing need to be accompanied by strong incentives to encourage the substantive cooperation necessary to actually spread the ability to adopt the relevant technology. It is difficult to imagine cases in which this might be carried out, particularly at a reasonable cost, but it should not be ruled out.

HELP FINANCE CROSS-BORDER TECHNOLOGY DEMONSTRATION AND COMMERCIALIZATION

Just as government support is needed to help inventions cross the valley of death between the idea and commercial application phases in the United States, government efforts are needed to aid commercialization across borders. While innovation now extends across national boundaries, with greater movement between developed and developing countries, inventions still tend to be commercialized in the advanced industrialized countries before being adapted to and deployed in the major emerging ones (although this is gradually changing).[128] This pattern, which slows the spread of technology, is likely to repeat itself in the case of low-carbon technology unless steps are taken to encourage the early commercialization of U.S. inventions in the major emerging economies. Indeed, while we saw some U.S. ideas being commercialized first in the major emerging economies—California-based Amyris's second-generation biofuels effort in Brazil is a striking example—it was much more common to see technologies diffuse internationally only after several product cycles.

The United States should support demonstration projects for not-yet-mature low-carbon technologies in the major emerging economies. If a certain technology is likely to play a major role in a particular major emerging economy but faces significant barriers at the demonstration stage that are unlikely to be overcome by the private sector alone, then the United States should seriously consider funding a demonstration of it in that country. Conducting such projects has clear potential benefits. First, since the challenges of moving a technology from the laboratory

to the field differ from country to country, demonstration projects that directly tackle those challenges in developing-world settings can resolve idiosyncratic barriers. Second, U.S. firms involved in demonstration projects can gain early insights into these emerging markets, an important competitive advantage at later stages of commercialization. Third, it may be cheaper and faster to build demonstration projects in the major emerging economies since these countries may already have not only considerable technical capabilities but also cheaper labor and capital costs—as well as more flexible regulatory environments.

Of course, not all investments in demonstration projects are equally wise. Demonstration projects require the cooperation of technologically sophisticated U.S. firms, which will participate only if they see commercial benefits. U.S. investment should thus be focused in the low-carbon sectors in which countries have shown a commitment to expanding demand and adopting relatively open approaches to foreign technology. The United States should also ensure that projects involve significant private sector financial contribution, which increases the chance that those projects have real commercial potential, reduces risks, and helps screen for promising opportunities; in addition, it should spread its funds among a range of technologies and firms. Washington should also strike a careful balance between insisting on a prominent role for U.S. firms and allowing the emerging economies to take part in a significant way. The United States has a reputation for being stingy on this account, and the big emerging economies can turn to other partners in Europe and Japan. Similarly, while the United States should insist on sharing financing responsibilities with host countries, it should be flexible, particularly with India, whose financial resources are relatively constrained.

The United States should be considerably more circumspect about providing financial support for cross-border commercialization. The government should encourage U.S. inventors to work with manufacturers in developing countries to commercialize U.S. inventions, just as it is exploring ways to encourage U.S. inventors to work with U.S. manufacturers to commercialize technologies. Such efforts would speed up the adoption worldwide of low-carbon technology by helping important technologies become commercialized earlier in major developing countries. Since commercialization efforts can create competitors for U.S. firms, however, several precautions are essential. First, the United States should emphasize efforts with India and Brazil, where the likelihood of creating competitors is lower than it is in China. Second, U.S. support

should be targeted to areas in which the deployment of technology would be significantly delayed if only U.S. firms were allowed to commercialize it. Third, the United States should place special emphasis on ensuring continued market access for U.S. companies to countries with which it cooperates on commercialization, so that cooperation is genuinely win-win. Once again, this suggests an approach that emphasizes cooperation with India and Brazil. Fourth, the United States should insist that emerging-economy governments significantly cofinance these commercialization efforts, particularly in China and Brazil, since these countries will likely reap significant commercial benefits from them.

FACILITATE CONTACTS BETWEEN U.S. INNOVATORS AND EMERGING-ECONOMY FIRMS

The United States has extensive consulting and financial services industries that connect entrepreneurs and companies. In the major emerging economies, these industries are considerably less developed. (This weakness is most acute in China and India.) This means that potentially valuable connections are often left undiscovered—and opportunities for mutually beneficial technology transfer are missed.

As far as their ability to connect different players go, governments cannot replicate the role played by the consulting and financial services industries. But the United States can help address the relevant gaps in at least two ways. First, it can help U.S. firms and innovators navigate the major emerging economies. The United States already has some valuable programs in this area. The U.S. Department of Commerce, for example, produces detailed guides for U.S. firms interested in exporting low-carbon products and services to China and India or in investing in those countries' low-carbon technology sectors.[129] It should extend that effort to Brazil and update its materials more frequently to reflect the rapidly changing conditions in these countries. (The two guides were last updated in July 2008.) The department also facilitates clean energy trade missions to China and India.[130] It should continue to conduct those missions, make sure to include companies that are precommercial, and explore expanding the program to Brazil.

Washington also needs to support centers that connect U.S. (and foreign) inventors with those who might be able to commercialize their ideas in the major emerging economies. India, with its "Climate Innovation Centers," has proposed a variation on this theme.[131] These

centers would house researchers and entrepreneurs for extended periods of time with the goal of identifying and pursuing productive relationships. (They would also be able to host people for shorter periods.) The United States has been supportive of the idea but has preferred an alternative that would create less substantial regional "hubs" that would host visitors for shorter periods of time.[132] The U.S. government should support the Indian approach both because it may be more capable of creating a wide range of connections and because, in an area so fraught with tension between developed and developing countries, it is especially important to support constructive ideas that come from developing countries.

USE FINANCE FOR U.S. TECHNOLOGY EXPORTERS TO SHAPE EMERGING-ECONOMY POLICY

The U.S. Export-Import Bank (Ex-Im Bank) helps U.S. exporters by financing overseas purchases of their products, while the U.S. Overseas Private Investment Corporation (OPIC) helps U.S. firms invest in overseas ventures by insuring them against political risk. Both organizations have embryonic strategies for promoting low-carbon technologies, which mostly consist of screening investments for emissions impact and rejecting the most egregious ones. The Ex-Im Bank, for example, recently refused to support a sale of coal-generation equipment to India until India agreed to also install renewable energy technology as part of the same project. Neither institution, however, works particularly aggressively to promote policy changes in foreign countries. The United States should take several steps to change that.

Both institutions provide services that reduce commercial risks, but neither provides additional support that closes the gap in cost between low-carbon technologies and more polluting options. If a country is creating low-carbon technology markets and is opening up its economy to commercial technology flows, Ex-Im should provide preferential financing that helps low-carbon options compete with fossil fuels, and OPIC should provide insurance against the risk that those markets will not materialize as the result of policy failures. (Congress should provide them with any additional authority that they require to pursue these missions.) Ex-Im, for example, should facilitate sales of solar technology to help the Indian Solar Mission by providing export credit for

U.S. wafer manufacturers, while OPIC should provide insurance for companies against the risk that the mission will be abandoned. These steps will require Congress to authorize them and, most likely, appropriate money for them. The steps will also require coordination with other developed countries, through the OECD, to ensure that they are not seen as promoting unfair competition and to avoid a race to the bottom (a process that is already under way) and with the major emerging economies to ensure that they are not seen as violating WTO rules. In interviews, however, officials and corporate leaders, particularly in India and Brazil, appeared to welcome additional financial support through this channel.

The United States should take such steps only if its counterparts are doing their part to create a hospitable environment for commercial technology diffusion. Currently, both the Ex-Im Bank and OPIC provide support even when recipient countries have policies that are hostile to trade and investment. The Ex-Im Bank, for example, will provide support to U.S. firms even if they are exporting to countries with high tariffs, which in practice simply transfers money between national treasuries. Washington should encourage countries that benefit from Ex-Im financing to reduce their barriers to trade in low-carbon technologies and press countries that gain from OPIC's insurance to lower their barriers to foreign investment in low-carbon technologies. When the United States is paying for not only commercial risks but also the extra cost of low-carbon technologies, it should go even further and require countries to adopt policies that enlarge markets for the relevant technologies. But the United States should be modest about what this strategy can accomplish. In particular, it should coordinate policy with other developed countries that might not require policy changes of technology recipients themselves, lest the United States undercut its own firms without prompting any significant change.

The United States should supplement support for firms through Ex-Im and OPIC with technical assistance through the United States Trade and Development Agency (USTDA). USTDA provides small-scale support for technical engagement on policy development in developing and middle income countries. Such support can help ensure that policies and regulations in the major emerging economies are as welcoming to foreign technology as possible. They will, however, overcome fundamental opposition to such openness.

MULTILATERAL INSTITUTIONS

Most of these efforts to promote technology transfer commercially and through government action can and should be pursued bilaterally. That would allow the United States to tailor its efforts to the specific technological and commercial circumstances presented by each country. It would also enable progress to take place outside the often poisonous discussions about technology transfer in the multilateral climate negotiations.

Nonetheless, it will be essential to integrate U.S. strategy with several multilateral institutions. The most obvious is the UNFCCC. Its deliberations have been largely focused, unhealthily and unproductively, on compulsory licensing. Other, more practical issues have proved harder to tackle, particularly because of the enormous variety of countries and circumstances involved, but also because of the perceived need to link progress on technology with a broader (and not forthcoming) global deal on climate change. That said, there has been considerable progress in discussions focused on creating a structure similar to the Climate Innovation Centers proposed by India. The United States should be willing to conclude a UNFCCC agreement that establishes such centers without waiting for a broader deal. But it should be realistic and not expect the UNFCCC to make much more progress on technology.

The United States will also need to work with the WTO. Multilateral pressure through the WTO can be much more effective at pressing emerging economies to relax unfair barriers to trade and investment than unilateral pressure from the United States. In some cases, the United States may even be able ally itself with some of the major emerging economies: in the past, the United States has shared with India concerns about unfair Chinese competition in solar technology and with Brazil concerns about unfair Chinese competition in wind turbine sales. And as it crafts guidelines for its own clean energy markets and works to promote its clean energy exports, the United States will need to steer clear of violating WTO rules itself.

The World Bank should also play an important role in U.S. strategy. The bank can be a useful forum for connecting U.S. export and technology assistance with policy reforms in developing countries. In May 2010, for example, the bank withheld financing for a supercritical coal plant in South Africa until Pretoria agreed to build more renewable capacity and reverse the growth in coal generation in the country.

Building support for such strategies at the World Bank will make implementing similar approaches in the United States at the Ex-Im Bank and OPIC less controversial. The World Bank can also be useful by financing the spread of technology in situations where U.S. financing would be politically impossible. For example, the World Bank has a project aimed at helping China better understand how to attract technology. (Its precise details are not yet public.) Indeed the United States has been successful in helping create the bank's Climate Investment Funds, which are helping finance the adoption of clean technology in the developing world.

Finally, the new Clean Energy Ministerial Process, launched in December 2009 by the United States, can play an important coordinating role in the United States' international technology strategy.[133] This process brings together energy ministers from roughly twenty countries to discuss and commit to voluntary policies that promote clean energy. (The first meeting was in the United States in July 2010 and focused mainly on coordinating energy efficiency policies; the second will be in the United Arab Emirates in the spring of 2011.) Ministers could use the meetings to coordinate their technology strategies so that they build on each other. The Indian Solar Mission, for example, will only be able to deploy large numbers of solar power plants if other countries drive down the cost of solar technologies and if Indian industries quickly absorb their innovations. That, in turn, will require investment in innovation, along with widespread deployment of the resulting technologies, in the rest of the world. The ministerial process is ideally suited for coordinating such interrelated national technology efforts.

CONCLUSION

A supply-side strategy aimed at accelerating the development and spread of low-carbon technology will not be enough alone to solve the problem of climate change. Ultimately, governments themselves must create incentives for people and firms to adopt those technologies. A comprehensive international technology strategy could accelerate innovation and lower the cost of low-carbon technology much more quickly than a policy that relies strictly on directly incentivizing increased demand. It could also make comprehensive efforts to adopt low-carbon technologies more politically attractive to policymakers

in developing countries. All of this, in turn, would make the necessary government incentives for technology adoption more likely.

In pursuing such a strategy, the U.S. government will need to be exceedingly careful to balance the United States' commercial interests with its climate interests. Yet there will be neither commercial gains from low-carbon technologies nor success in cutting carbon emissions unless the market for low-carbon technologies is massively expanded. By focusing on this bottom line in developing its international technology strategy, the United States can strengthen the global response to climate change while safeguarding its own prosperity.

Appendix: Case Studies

The broad findings in the body of this report are supported in part by detailed case studies. These case studies are the product of fieldwork in Brazil, India, and China and research in the existing scholarly and popular literature. The results presented here are used throughout the report.

ONSHORE WIND IN CHINA, INDIA, AND BRAZIL

Onshore wind is the most mature renewable energy source available. The different experiences of China, India, and Brazil in building wind industries thus offer insight into the different ways that technology transfer can happen and the outcomes that can result.

Wind power is central to China's plans for nonfossil energy to provide 15 percent of the country's energy supply by 2020. Although wind currently accounts for less than 1 percent of China's total electricity consumption, the country has been adding capacity aggressively in recent years. By 2009, China's installed capacity totaled 25.9 gigawatts, second only to the United States, and in 2009 alone, Beijing installed about 14 gigawatts, one-third of the additional capacity installed that year worldwide.[134] By 2020, China aims to have increased its wind power production capacity by a factor of five.[135]

Beginning in 2002, Beijing passed several laws and regulations concerning wind power, including the Government Procurement Law, the Wind Power Concession Project, and the Notice of Requirements for the Administration of Wind Power Construction. The country's 2008 fiscal stimulus package also boosted its wind industry. Over time, these regulations and financing mechanisms have enabled China to develop a wind industry that is almost entirely domestically driven.[136] One regulation, for example, required that any wind farm constructed in China

meet a 70 percent local content requirement; as a result, the share of China's wind power equipment purchased from abroad dropped from 75 percent in 2004 to 24 percent in 2008.[137] By 2009, the foreign share had dropped to 12 percent.[138] In fact, under the 2004 Wind Power Concession Project (designed to promote large-scale wind farms), no foreign firm has succeeded in selling equipment in China.

China indigenized technology primarily through licensing: the story of China's second largest turbine manufacturer, Goldwind, provides some insight into how this happened.[139] Companies like Goldwind benefited from China's growing domestic market, combined with unofficial preferences for Chinese-owned technology (even over technology made in China by foreign firms). The Chinese government's 863 Program also helped create a technological base by supporting R&D. Goldwind "first obtained its wind turbine technology through purchasing a license from Jacobs, a small German wind turbine manufacturer that has since been purchased by REpower, to manufacture 600 kW wind turbines."[140] It also "obtained a license from REpower for its 750 kW turbine, and a license from another German company, Vensys Energiesysteme GmbH, for a gearless 1.2 MW turbine."[141] In addition to obtaining licenses from these companies, Goldwind worked with them actively. The last license, however, "prohibits Goldwind from exporting turbines." Over time, local suppliers became steadily stronger: "Goldwind reportedly now uses locally manufactured generators, gearboxes, control systems, blades, yawing systems, hubs, and towers for its turbines, while purchasing several of its components from domestic suppliers."[142] The company also sends its staff abroad for training.

While the Chinese policy of enforcing strict limits on foreign content produced some short-term victories (such as the growth of Goldwind), in the process, quality has suffered. Without significant foreign competition or openness to the best foreign technologies, Chinese turbines are, according to Chinese experts, not up to international standards, and Chinese firms have yet to produce more complex pumps and tubular turbines.[143] These quality problems hamper the growth of wind energy in China and frustrate hopes that the Chinese economy's current overcapacity will be partly alleviated through exports.[144] According to one Chinese analyst, "Fixing problems at overseas installed turbines will be much more expensive and overseas customers have higher expectations on reliability, so overseas expansion will be tough for Goldwind."[145] Lu Yachen, the vice president of Shanghai Electric

Group Corp., said that China is unlikely to export more wind turbines now because "homegrown technology is not as competitive."[146]

Despite these problems and despite the potential value of a greater international presence in solving them, the role of multinational corporations in China's future wind development is uncertain. Some companies have withstood the vagaries of shifting Chinese regulations: Tang Energy, for example, has managed a successful joint venture wind turbine factory outside Beijing for many years, while American Superconductor sells the electrical control systems for the 3-megawatt and 5-megawatt turbines of one of China's largest wind developers, Sinovel. And as China's State Grid proceeds with plans to spend more than $600 billion by 2020 to build smart power grids, companies such as GE are establishing smart grid R&D centers in anticipation of future business opportunities. But the commitment of the Chinese government to protect the wind industry from an already mature foreign industry has not wavered, with sometimes capricious new regulations adding further obstacles to the diffusion of technology.

Meanwhile, the government is still pushing exports. The China Development Bank, for example, has given Goldwind a $6 billion credit line to boost international sales, invest in overseas wind farms, and provide credit to overseas customers. In addition, according to Shi Pengfei, the vice chairman of the China Wind Power Association, the China Export-Import bank is now providing loans for wind power projects in Africa. But as it tries to break into the U.S. market, China will face challenges. According to the U.S. partner of a joint venture wind turbine firm, the challenge for China will be to learn the rules of the game. Even though there are no formal local content requirements in the United States, the Chinese will need to actually invest in the United States, building facilities to manufacture there and not simply bringing their equipment and money.[147] At least one Chinese wind firm has already learned this lesson: the Shenyang Power Group, after encountering significant political opposition to its plan to invest in and build its first wind farm in the United States, is now building a wind turbine factory in Nevada.

The story of wind energy in India is decidedly different: the Indian industry has been, and continues to be, supported by a mix of domestic and export markets, and it has grown up in a much more open environment. Wind energy is India's fastest growing and technologically most advanced renewable energy sector. In the past decade, output

increased twelve-fold while the cost of generation was cut in half. In 2009, India ranked fifth in installed wind energy capacity, after China, the United States, Spain, and Germany. The growth of the industry has been hampered by inconsistent government support: the main driver has been a tax incentive whose value fluctuates wildly with business cycles. Indeed, most policymakers and businesspeople outside the wind industry predict that wind will not be a major long-term player in addressing India's energy needs. They point to limits on the available wind resources and to the greater potential, in their eyes, of solar energy.

India's Eleventh Five Year Plan set a target to increase the installed capacity of renewable energy (excluding large hydroelectric plants) to 23,500 megawatts by 2012—or more than 10 percent of total installed capacity, with wind comprising 72 percent. In order to promote private investment in the sector, the government has initiated several fiscal and financial measures, including an accelerated depreciation allowance of 80 percent, a concessional import duty on certain components of wind electric generators, and a ten-year income tax exemption for wind companies. The Indian Renewable Energy Development Agency under the Ministry of New and Renewable Energy has provided long-term, low-interest loans and financed sixty projects between 2006 and 2008. In December 2009, the government introduced the Generation Based Incentive, which will pay Rs 0.5 ($.01) for every kilowatt-hour of electricity fed into the grid from wind power projects. The Ministry of New and Renewable Energy has earmarked 3.8 billion rupees ($81 million) and, depending on its performance, the incentive may be scaled up through 2012.

Unlike China, India has emerged as a leading wind turbine supplier. Suzlon, based in Pune, is the world's third-largest wind turbine manufacturer, behind Vestas (Denmark) and GE (United States). Now, after acquiring the German company REpower in 2006, it has a 9.8 percent share of the global market.[148] It has substantial manufacturing facilities in India, the United States, Belgium, and China, and about 90 percent of its orders come from markets outside India (largely from the United States, South America, and China). But questions have been raised about the quality of Suzlon's turbines. In 2008, Edison Mission Energy, Suzlon's largest U.S. customer, canceled an order for 150 turbines after the rotor blades developed cracks.[149] Customers worldwide have

complained that Suzlon's turbines fail to generate the expected amount of electricity, suffer from excessive vibrations during high winds, and have control-system problems.

Indian government incentives have also drawn multinational companies to India's wind sector. Traditionally, Indian turbine providers have been joint ventures, with the foreign partner as the majority shareholder, and have focused on adapting turbines to the Indian market. After India changed its subsidy program to reward the amount of wind energy generated rather than the number and size of turbines installed—a shift that benefits makers of high-quality turbines—GE announced it would revive its business after a four-year absence.[150] Vestas has plans to nearly double its capacity to 500 megawatts in the next three years, and recently located its largest R&D center outside Denmark near Chennai, where it is able to take advantage of low-cost mechanical engineering and (slightly more expensive) information technology talent. The decision to place the R&D center in India was made with exports in mind, not the appeal of the Indian market, and other foreign companies have long-term plans to export wind turbines using India's low-cost engineering base.[151] In February 2010, Siemens announced that it will invest Rs 16 billion ($346 million) over the next three years and that about a third of the investment would be directed toward developing wind turbine technology. The resulting products are expected to launch by 2012.

Indigenous Indian wind technology efforts, though, are weak. Indian universities and companies do not seem to be conducting R&D at any scale, and the government's Indian Center for Wind Energy Technology (CWET) is concerned mainly with inspections, licensing, and training. While CWET has attempted to work on R&D together with multinational corporations and domestic wind companies, its staff argues that those partners have rejected cooperation out of concern about intellectual property; the potential partners insist that there is simply no technical or business value to working with CWET.

While India has fostered the growth of internationally competitive turbine exporters and China has installed world-leading amounts of wind capacity, Brazil has, until recently, been stagnant on both fronts. Brazil possesses the greatest wind power potential in Latin America and the Caribbean: the Brazilian Planning Ministry estimates that the country's onshore wind power potential may reach 350 gigawatts—or

three times the current capacity of all energy sources in Brazil. (Other estimates are considerably lower.)[152] To date, however, Brazil has less than 1,000 megawatts of installed capacity.[153]

Until recently, there was little impetus for Brazil to build wind capacity. But hydropower shortages have focused government attention, and wind power, because it complements the current hydroelectricity, is becoming increasingly attractive. When Brazil is at its driest—and producing the least hydropower—it is also at its windiest, providing a potential clean option for addressing the challenge of ensuring stable access to electricity.[154] The windiest locations in Brazil also happen to be in the politically powerful, but economically underdeveloped, northeast of the country. The downside, however, is that electric distribution infrastructure is weak in this region. Moreover, there is disagreement within the government about the importance of wind power, with some touting its critical role and others dismissing it as marginal. Brazil's current government has tried to develop the wind sector by creating more attractive demand-side policies. Its first serious effort to promote wind power began in 2002 with the Programa de Incentivo às Fontes Alternativas de Energia Elétrica (PROINFA). The goal was to encourage renewable electricity (wind power, solar power, and small-scale hydroelectric power) through mandates and incentives, including preferential financing from the Brazilian development bank (BNDES) and guaranteed preferential purchase pricing by the government. Yet wind energy was slow to take off; eight years later, it amounted to less than 1,000 megawatts of capacity. Domestic content requirements, as well as requirements that favored certain regions of the country, slowed international interest and the flow of technology. So did the initial small scale of operations, which made it less attractive for foreign companies to invest substantially in local production facilities.

In 2009, the Brazilian government phased out PROINFA in favor of a new strategic approach, based on repeated public auctions of the right to sell electricity. In the first round, which took place in December 2009, the government successfully sold nearly 1,800 megawatts of capacity, which will come from seventy-one new projects. The winners included international players such as Portugal's Martifer and Energias de Portugal, Electricité de France, and EnerFin of Spain.[155] And they included domestic developers such as Dobreve Energia and Renova Energia of

Brazil (which both elected to use General Electric's 1.5-megawatt class wind turbines). The government has announced plans for regular auctions in the future and expects to sell some 10 gigawatts over the next decade, increasing wind power's share of the country's national electricity to approximately 4 percent by 2019.[156]

Domestic content laws also changed in Brazil, allowing large turbines (over 1,500 kilowatts) to be imported from abroad and eliminating tariffs on large imported turbines.[157] Still, industry insiders confirmed that BNDES still requires that these ventures contain two-thirds domestic content if they are to receive preferential financing. The push for local production comes more from Brazil's desire for jobs than from any desire to control intellectual property, so, as in other industrial sectors, the Brazilian government seems satisfied with foreign ownership of new plants and factories. (That said, a senior official at one foreign corporation noted that it was required to bring its most advanced turbines to Brazil as a condition of BNDES support, demonstrating that Brazil sometime does care strongly about attracting cutting-edge intellectual property.) Moreover, with a large and stable domestic market, companies find it uneconomical to ship blades for large turbines rather than manufacturing them domestically. The government plans to use its financing tools to regulate competition—for instance, if near-monopolies develop, then the government will lift its requirements that projects contain a certain amount of domestic content in order to receive subsidized financing. Indeed, in August 2010, steelmakers appeared to be squeezing wind turbine producers by raising their prices; BNDES responded by threatening to waive local content requirements.

The fundamental challenge for building a substantial wind energy industry in Brazil remains cost. The 2009 auction awarded twenty-year contracts at a price of 189 Brazilian reais per megawatt-hour ($102 in U.S. dollars), still higher than the price of hydro- or coal power (although the differential is shrinking). This leaves in question the future of the industry if left to the market. As in biofuels, the success of wind power will depend on the Brazilian government making a long-term commitment to make investment in the sector economically and politically attractive relative to other sources. Foreign manufacturers will continue to hedge their bets by maintaining a presence in export markets rather than just in the domestic market.

THE INDIAN NATIONAL SOLAR MISSION

In early 2010, Indian Prime Minister Manmohan Singh announced the National Jawaharlal Nehru Solar Mission, a thirty-year, $19.25 billion program that aims to expand Indian solar energy capacity to 20 gigawatts by 2022 and turn the country into a global leader in solar manufacturing and technology. While abundant sunlight in much of India makes solar power a potential answer for the rising energy demand, most of the solar power generated in India today is not connected to the central grid. Of the 100 megawatts of solar capacity installed in India as of late 2009, 97 percent remained off the grid.[158] The National Solar Mission plans to address this issue by enacting renewable purchase obligations (which require utilities to generate a minimum fraction of their electricity from renewable energy) and preferential tariffs in a three-phase plan. The first phase, from now until 2012–2013, will concentrate on "capturing the low hanging options" in solar thermal power, reaching the rural population through off-grid systems, and minimally increasing the capacity of grid-based systems. In the second phase, "capacity will be aggressively ramped up." This will be supported by a feed-in tariff (i.e., a high guaranteed electricity price) of 10 rupees per kWh ($0.20) for urban areas, and 11 rupees ($0.22) per kWh for rural areas.[159]

This plan is matched by a major push on the innovation and manufacturing side of solar power. During the last two to three years, the number of suppliers of solar PV modules and cells in India grew from ten to more than thirty. The country's capacity to produce modules, just 60 megawatts in 2005, increased to over 1 gigawatt in 2009 (primarily for export). Analysts project that India's solar industry, increasingly driven by domestic consumption, will generate $3 billion (14 billion rupees) of revenue by 2013. Meanwhile, there are high hopes for concentrated solar power (CSP) in India, which could benefit from the country's large pool of engineering talent. The California-based group e-Solar, for example, has a 2.5-megawatt plant under construction in Rajasthan and is planning a 46-megawatt plant. Still, suppliers are limited (especially compared to the number of PV suppliers), transmission is difficult, and prices are falling slower than they are in PV. It is also difficult to obtain financing. As Banmali Agrawala, the executive director of strategy and business development at Tata Power, said, "The challenge is to get the balance on a commercially viable price—one that is

high enough to create incentive but low enough to only attract the serious players."[160]

The transfer of solar technology between the developed markets and India has occurred through multiple channels. Tata-BP Solar, which was established in 1989 and develops solar PV and thermal products, is a joint venture. Moser Baer PV, which manufactures 90-megawatt polycrystalline PV cells and 50-megawatt thin-film cells, received foreign investment from Nomura, CDC Group, Morgan Stanley, and Credit Suisse.[161] As large companies such as Reliance and Mahindra move into solar power, they are hiring many former employees of BP-Solar. As a result, knowledge gained by those workers ("tacit knowledge") spreads.[162]

Most of India's solar products are exported to Europe, Japan, and the United States. Approximately 60 percent of Tata-BP Solar's sales, for example, come from abroad.[163] While Indian manufacturers focus on the simpler and lower value-added parts of the supply chain, they are highly dependent on imports for critical raw materials, such as silicon wafers, which are used for solar cells and panels. Indian experts and businesspeople believe that it will be difficult for India to compete with China and Taiwan on this front, since the others enjoy efficiencies of scale provided by their much larger semiconductor industries.

The National Solar Mission will continue to support cell and module manufacturers by eliminating duties on capital equipment and raw materials, exempting them from excise duties, and offering them low-interest loans. For its first two years, the program has also imposed strict local content requirements on PV systems. Foreign companies are "expected to procure their project components from domestic manufacturers as far as possible," and by 2011 will be banned from using foreign-made solar modules and, by 2012, from using foreign-made cells.[164] Although both Tata-BP Solar and Moser Baer announced expansion plans in response to the National Solar Mission, they are at a disadvantage in terms of resources and know-how and would have to compete with bigger foreign firms for contracts with solar developers. While India's solar push may cause a shift to domestic production over the long term, Charles Yonts, a solar analyst with CLSA, projected that Chinese and Taiwanese firms will benefit from the effort in the short run.[165] But since Yonts made his projection, local content requirements have remedied the situation he described. Aimed primarily at shutting out Chinese manufacturers, these measures were

lobbied for aggressively by Indian manufacturers, and foreign governments are pushing back against them. No local content requirements were imposed for concentrated solar thermal power, since basic economics will ensure that the bulky technology is primarily provided by domestic firms.[166]

Indian policymakers and businesspeople largely recognize that the National Solar Mission can succeed only if other countries make big investments in solar electricity themselves. The mission plans to deploy 1 gigawatt of capacity by 2013, another 3 gigawatts by 2017, and a final 16 gigawatts between 2018 and 2022. Unless the cost of grid-connected solar drops to near parity with other sources, though, the government will not be able to afford subsidies for the last stage. Analysts consistently note that the amount of solar energy planned for India is not enough to generate the needed cost reductions. Thus India's mission, if it is to be sustainable, requires both that solar power becomes much more popular elsewhere in the world and that India absorb the innovations developed elsewhere (and benefit from the economies of scale that global deployment generates).

ADVANCED CLEAN COAL TECHNOLOGY IN CHINA AND INDIA

Concerns about energy security and electricity costs have led both China and India to focus their electricity generation efforts on coal. Each has made concerted efforts to deploy supercritical and ultrasupercritical pulverized coal technology, which operates at extremely high temperatures and pressures to improve the efficiency of combustion. (China's effort is decidedly more aggressive and better developed.) Beyond that, technological efforts to reduce emissions have focused on CCS technology, which could reduce carbon dioxide emissions by as much as 90 percent, and IGCC technology, which holds the (as yet unproven) promise of higher efficiency and can reduce the costs of building an integrated system that includes CCS. Neither of these technologies has been commercialized yet, and China and India have adopted different approaches to develop and deploy them.

China has focused much more intensely on CCS than India has. It first began to pursue CCS as a way to mitigate climate change in 2005, when the Ministry of Science and Technology (MOST) designated it a

"cutting-edge technology." From 2008 to 2010, Beijing spent $43 million on R&D for CCS through its 863 Program. As a group of Stanford researchers note in their comprehensive study of CCS's potential in China, these policies supported the development of technology but not its deployment.[167]

Several IGCC demonstration projects currently under way in China could make use of CCS technology when it becomes available. GreenGen, perhaps the most prominent of these efforts, aims to build a "commercial-scale, near zero-emissions coal-fueled power plant with carbon capture and storage."[168] The project is a partnership between China Huaneng Group, which holds the majority share, and eight other companies, including seven Chinese energy companies; the U.S. coal company Peabody Energy, which has its own IGCC operation in the United States, is an equity partner in the venture. A $135 million loan from the Asian Development Bank (ADB) supplements the funding from these companies. The first phase of the project is set to be completed in 2011 and should be capable of generating 250 megawatts of power.

The technology for the GreenGen plant is Chinese, even though China has been open to IGCC technology from other countries. Of the ten IGCC power generation projects planned or under construction in China, seven use foreign technology, while three use Chinese gasification technology. Huaneng, in fact, is already beginning to export its IGCC technology. Plans for a Canadian-U.S. IGCC plant are under way in Pennsylvania; the project will use IGCC technology from the Thermal Power Research Institute in China—the same Huaneng-controlled entity that is providing the technology for GreenGen. In 2010, however, the U.S. Department of Energy did not select the plant for funding under its Clean Coal Power Initiative. The company behind the project, Future Power PA Inc., must still arrange additional financing if plans for the plant are to move forward.

Despite China's jump into CCS, many analysts and businesspeople harbor serious doubts about its commitment and capacity to develop CCS into a viable strategy to mitigate climate change. According to one well-placed U.S. businessman based in Beijing whose view is broadly representative, while China has the engineers, steel, and cement to develop IGCC and CCS, it lacks the right policy environment to support the risks involved. The viability of GreenGen, therefore, will be an important signal for the future of CCS in the country. Any additional

demonstration projects would require substantial government investment, which so far does not appear to be forthcoming.

Other analysts reinforce that realization with a broader concern that CCS has limited viability past the demonstration stage. Ashok Bhargava, a senior energy specialist at the ADB, has argued that "the Chinese government hasn't shown clear longer-term vision at the moment to adopt the technology." Ma Zhong, the president of the Institute of Environmental Studies at Renmin University, believes the cost is simply too high, in large part because the core technologies are foreign owned. "Although CCS is the most efficient coal clean technology, there are various other low-cost technologies enabling a reduction in emissions that have yet to be fully applied in China," he has said. "CCS isn't an economic option suited to China's conditions. China doesn't own the core technologies for CCS so it would generate high costs in transferring the patented technologies."[169] There is no concrete evidence to support this concern, but it reflects broader worries in China about dependence on foreign technology. Such thinking is backed up by research done by the Stanford group, which argues that underlying the push for CCS is the country's desire for energy security: "diversity of energy supply, reliable and cheap electricity and the development of domestic intellectual property for energy technologies." It suggests that while such drivers augur well for CCS demonstration projects, there are structural disincentives to scaling up the technology beyond the demonstration project phase.[170]

India has focused almost exclusively on IGCC, to the exclusion of CCS. Indian policymakers see little chance of deploying CCS domestically because of both cost and limited (and low-quality) domestic coal resources. Unlike China, though, they do not see an opportunity to commercialize and export CCS technology either. India's ICGG efforts, however, lag far behind those in China or the West. The Indian government has long been concerned that foreign firms have little interest in developing IGCC technology that is compatible with low-quality Indian coal. Instead, it has put its weight almost entirely behind domestic efforts. This has focused on a 6.2-megawatt demonstration project built and operated by the state-owned engineering and manufacturing firm Bharat Heavy Electricals Ltd. (BHEL), which was commissioned in 1989. (The deep involvement of BHEL has probably reinforced a prejudice toward domestic technology, since state-owned enterprises tend to have much stronger biases against foreign technology than

private firms do.) After several years of abortive efforts, the firm is just now attempting to scale up to a 120-megawatt commercial demonstration plant; construction has finally begun, with the Indian government contributing 3.5 billion rupees ($83 million)—roughly the difference between the cost of the IGCC project and a conventional coal project of similar size.[171]

The United States, in contrast, has two commercial IGCC demonstration plants: one 262-megawatt plant that has been operating since 1995, and a 250-megawatt plant that has been operating since 1996.[172] (There was also a 110-megawatt plant that operated from 1984 to 1989.[173]) The 250-megawatt project uses technology owned by GE, which has substantial operations in India (including employees with expertise in IGCC), suggesting that GE could cooperate in the Indian efforts if there was appetite on the Indian side.[174] Indeed, USAID has long helped India evaluate a variety of IGCC technologies, including U.S. technologies. India has, however, consistently been suspicious that such "help" was in fact biased toward U.S.-owned technologies.[175]

By largely closing itself to foreign technology, India has not been able to fully benefit from IGCC innovation elsewhere. This contrasts with China, which has been able to leverage foreign IGCC technology (though not as much as it might have liked to). Combined with the high capital costs of IGCC, which are particularly burdensome in capital-poor India, this lack of openness means that it will be a long time before IGCC technology is commercialized or deployed in India.

ELECTRIC VEHICLES IN CHINA

By 2020, the number of Chinese cars on the road is expected to exceed three hundred million. China's leaders have thus made hybrid electric and electric vehicles (EVs) a core element of their energy and environment strategy over the next five years. By 2015, they plan to have five hundred thousand to one million "new energy" vehicles on the road, including EV hybrids and fuel cell vehicles.

China is putting enormous effort into its electric vehicle industry. In August 2010, Beijing announced that a group of sixteen SOEs planned to form an alliance to conduct R&D for, and set standards for, electric and hybrid vehicles. The Chinese government reportedly plans to invest almost $15 billion in the alliance.[176]

Already, China has been pushing forward a deployment strategy that would also build a strong technology and manufacturing base in the country. The State Grid Corporation of China and Southern Power Grid plan to ramp up their construction of charging stations: by 2015, the government anticipates four thousand recharging stations throughout China (although only seventy-five are targeted for construction in 2010). Equally important, in June 2009, the Ministry of Finance announced new subsidies to the finance bureaus of provincial and municipal governments for plug-in hybrid and electric vehicles. These subsidies, which target five cities, will be as high as $8,000 for plug-in hybrids and more than $9,000 for electric vehicles. Beijing has also tied in some quality control standards to the subsidies: the batteries must have a life span of more than five years or 100,000 kilometers.

Each of the five cities (Shanghai, Changchun, Shenzhen, Hangzhou, and Hefei) boasts the headquarters of one of China's major automakers. Some of these cities are tacking on their own subsidies to help encourage green car purchases: Shenzhen has promised to provide an additional subsidy of approximately $3,000, while Shanghai will waive its $4,000–$5,000 fee for license plates. Beijing is planning to offer electric vehicles discounts on parking and highway tolls. Cities also are likely to provide a competitive advantage to the automobile companies located in them. Shenzhen, for example, plans to buy two thousand electric taxis from its hometown favorite, BYD, the world's largest manufacturer of rechargeable batteries for cell phones and laptops, and the Pengcheng Electric Taxi Company, a subsidiary of the Shenzhen Bus Group, is working with BYD to establish an electric vehicle servicing company.[177] These subsidies are a significant boon to the carmakers. According to one BYD official, they will cover almost one-third the price of its F3MD hybrid model.

But the subsidies may not immediately expand EV manufacturing. More than a decade ago, the Chinese government gave one battery company, the Lishen Battery Joint-Stock Company, millions of dollars in subsidies to develop and produce lithium-ion batteries; the company now has $250 million in annual sales, and recently received a $2.6 million 863 Program grant to start making electric cars.[178] So far, however, the government's electric car subsidies have not elicited the same interest from Chinese carmakers. BYD, for example, is not increasing its manufacturing in response to this subsidy. Chinese consumers, concerned about the driving range of the battery, access to charging

stations, and the reliability of the cars, have lagged far behind the government in their enthusiasm for clean energy vehicles.[179] BYD's much-touted E6 electric vehicle reportedly travels 300 kilometers on a single charge. But there has been no outside verification of the car's battery power, and sources at the China Automotive Technology and Research Center say that no domestic-made electric vehicle that has been tested has simultaneously met targets for driving range, battery weight, failure rate, maximum speed, and battery life.[180]

Already, the United States and China are cooperating on electric vehicles. While an effort initiated under the George W. Bush administration between the cities of Chongqing and Denver stalled due to lack of interest,[181] the United States and China have made progress on other fronts and are aiming to establish "joint standards for plugs, battery test protocols, joint demonstrations to compare how plug-ins will be used and a joint technical roadmap to plan out what research needs to be done and how it can be used to bring EVs to market." The two countries have planned EV demonstration programs in more than a dozen cities, where they will share data on charging patterns, consumer experiences, and integration of EVs into the electric grid.[182] This type of cooperation could help China overcome its proclivity to set standards that keep foreigners out of its markets.

U.S. and Chinese electric vehicle companies are building partnerships that could foster opportunities for actual investment and joint development; the sharing of technological advances between the two sides will enable each to benefit from the R&D of the other. Such partnerships take a wide range of forms. The American financier Warren Buffett owns a 10 percent stake in BYD, which is establishing a headquarters in Los Angeles.[183] The California-based company Better Place and the Chinese company Chery Automotive Co. are developing electric vehicle technology together, matching up Better Place's battery switch technology with Chery's cars.[184] The work of another California company, Coda Automotive, shows how the relative strengths of different countries can help produce an innovative product. Coda's all-electric car, which is scheduled to be brought on line in late 2010, uses batteries from China, a chassis from Japan, and a battery pack designed in the United States. Kevin Czinger, Coda's president and CEO, believes that the combination of U.S. engineering and Chinese willingness to spend quickly on infrastructure is the best way to succeed in the electric vehicle business.[185] Given that electric-vehicle technology still

largely comes from outside China, concerns about intellectual property remain. Toyota, for example, is reportedly readying a case against BYD—notorious for its reverse engineering practices—for patent infringement.[186]

Still, even as the technology remains immature, China's EV companies are already looking to foreign markets. China Ankai Automobile, based in the province of Anhui, is developing a plug-in hybrid electric bus for the U.S. market. It is working with the U.S. company Efficient Drivetrains to develop the plug-in hybrid's drivetrain, and representatives from Ankai and government officials from Anhui have visited Atlanta and Tennessee to learn about transportation systems, U.S. regulations, and market opportunities. Ankai would likely import the bus shell but establish an assembly plant in the United States; Buy America rules stipulate that in order to take advantage of federal funding for transit buses, 60 percent of the parts must be sourced domestically.[187]

BRAZILIAN BIOFUELS

Brazil is the largest ethanol exporter in the world and is second only to the United States in ethanol production. Ethanol delivers 20 percent of Brazil's total transportation energy needs and nearly 50 percent of its light vehicle fuel demand.[188] Although the industry is based primarily on domestic technology and domestic markets, it is increasingly incorporating foreign technology and looking to much larger export markets.

The creation and expansion of Brazil's sugar-based ethanol industry over the last three-plus decades is credited with reducing the country's dependence on foreign oil, greening its energy supply, and fomenting a sophisticated homegrown biotechnology industry.[189] Brazil's biofuel program began in 1975 under military president Ernesto Geisel, as a response to the steep drop in world sugar prices in 1974 and the 1973 oil shock. The National Alcohol Program (Programa Nacional de Alcool, or Pro-Alcool), as it was called, incentivized the use of ethanol by offering low-cost loans and credit guarantees, mandating that gasoline contain a certain percentage of ethanol, setting favorable purchase prices by the government, and guaranteeing monopolistic distribution by the state-owned energy company, Petrobras. Pro-Alcool fit squarely

in Brazil's strategy to develop domestic industry through active industrial policy. It was also a boon for sugar producers, a powerful (and generally conservative) domestic constituency. Indeed, most Brazilian observers see the government's promotion of ethanol as sugar policy first and energy policy second. In the first ten years of the program, the production of ethanol flourished, growing to nearly half of Brazil's liquid fuel supply.[190]

With the 1980s financial crisis, many of ethanol's subsidies disappeared, and in the 1990s the opening of Brazil's economy meant that there was little support for a return to strong intervention in the biofuels sector. Ethanol production fell. But the government continued to require all gasoline contain 20 percent ethanol, maintaining a baseline of support for the industry. In the early 2000s, the introduction of domestically developed flex-fuel technology by the auto industry (which is dominated by foreign manufacturers) helped boost ethanol consumption. These car engines—which today constitute over 90 percent of car engines produced in Brazil—can switch to any blend of ethanol and gasoline, allowing the consumer to shift among different fuels depending on prices. While the ethanol market today is largely free and competitive, the government still provides some benefits and incentives. These include taxing ethanol at a lower rate than gasoline, as well as government-mandated blending ratios, which often rise and fall depending on gas and sugar prices.[191]

The Brazilian government has helped promote innovation by guaranteeing markets and thus removing some risk for firms. The deregulation of the sugar and ethanol industries has also stimulated innovation, both in technology and management, leading to large improvements in ethanol-related productivity. The increased competition that has resulted has driven firms to acquire more advanced technology. Deregulation has also spurred a move toward larger and more professional growers and mills, away from small and family-owned mills, which are seen, with some justification, as conservative and thus unwilling to invest in technology. As the biofuels industry consolidates under larger national and international players, not only will economies of scale improve productivity but the transfer and use of technology will increase, too. Large modern firms are more likely to adapt new technology, such as new varieties of sugarcane, new harvesting or milling processes, or new management and supply chain processes.

The government has supported the ethanol industry by directly investing public money in R&D to increase the efficiency and productivity of sugar cane production. It has also funded several high-quality university research initiatives on sugarcane biotechnology. While many of these efforts are perceived by those in the biofuels industry as overly academic, they have produced a base of technically skilled talent that has been valuable to industry more broadly. The industry has also benefited from the Center for Sugarcane Technology (CTC), which develops more productive sugarcane varieties. Its close relationship with industry and lack of government involvement make it particularly well positioned to adapt technology for industrial use. The center's recent partnerships with BASF and Novozymes, among others, speak to the international acknowledgment of its quality, as well as its participation in the cross-border transfer of commercial technology. Companies working with the center report that they have not held back from participating for fear that they would forfeit control of their intellectual property.[192]

Start-ups are also playing an increasing role in Brazilian ethanol technology and in international technology transfer. Two small sugarcane biotechnology companies, CanaVialis and Allelyx, received seed capital from the Brazilian conglomerate Votorantim in 2006 and were bought by the U.S. firm Monsanto in 2008. (CanaVialis also provides interesting evidence for the benefits of doing certain R&D in the developing world: its breeding program is dominated by relatively low-paid high school graduates, rather than by PhDs.[193]) When Cosan, the leading Brazilian ethanol company, entered into a $12 billion joint venture with Shell, Shell contributed its share in two small U.S. and Canadian ethanol biotechnology companies to the deal. The U.S. start-up Amyris, meanwhile, has opened up shop in Brazil, hoping to develop its technology in the low-cost Brazilian market before debuting it in the United States. Amyris has taken advantage of the concentration of ethanol talent in São Paolo state—in fact, its offices are just across the street from CanaVialis and Allelyx.

This cross-border activity has not occurred without controversy. Some Brazilian federal policymakers greeted the acquisition of CanaVialis and Allelyx with considerable concern, and similar worries were voiced in the wake of the Shell-Cosan deal. Rather than explicitly erecting barriers to foreign participation in the Brazilian industry, though, the government has responded by pressing the state oil company,

Petrobras, and the state development bank, BNDES, to take greater stakes themselves in the ethanol industry. This could push out foreign participants at the expense of international technology transfer.[194]

To date, Brazil's efforts have focused almost entirely on first-generation biofuels. Second-generation biofuels, which have been a central focus for technologists in the United States, have attracted less interest for several reasons. It is still far cheaper to produce ethanol from sugarcane than it is to produce second-generation ethanol from other materials, an advantage that is expected to persist indefinitely. Producers might be able to exploit second-generation technology to produce ethanol from sugarcane bagasse, but they already have another use for that material: the generation of electricity.

Instead, second-generation ethanol appears to be attractive primarily from an export perspective. Brazil expects to export only a small fraction of its ethanol—unless, several observers report, it is able to produce large quantities of second-generation ethanol. Being able to produce second-generation biofuels would assuage Brazilians' concerns that international standards for sustainable biofuels will penalize first-generation sugarcane ethanol. For the same reason, Brazilians actively participate in standard-setting efforts while hedging their bets by investing in second-generation fuels. These investments have taken form most prominently in Brazil's new Center for Ethanol Biotechnology (CTBE), which is focused on second-generation research to prevent Brazil from being left behind if breakthroughs in second-generation biofuels occur. The CTBE is cooperating with industry and with foreign research organizations, including the U.S. National Renewable Energy Laboratory (NREL).[195]

Brazil's biodiesel efforts are far younger and less advanced than its ethanol efforts. They focus on providing rural employment, and, as a result, government support comes with requirements that producers use soybeans grown by small family-run soy farms. That, in turn, makes the absorption of advanced technology exceedingly difficult (despite government efforts to provide technical training to farmers). Not surprisingly, most observers have low expectations for Brazilian biodiesel production.

This weakness, though, is an exception. The Brazilian bioethanol industry is largely a model for the development and transfer of low-carbon technology.

DEFORESTATION IN BRAZIL

Deforestation accounts for roughly half of Brazil's greenhouse gas emissions. It is primarily seen as a policy and regulatory challenge, particularly by the international community, which has pressed Brazil to bar, or at least limit, deforestation. But the social and economic drivers of deforestation suggest that part of the answer lies in technology. Brazilian deforestation is not caused primarily by logging. It is driven by ranchers, who clear land to create new pastures. Those ranchers, in turn, are often provoked by farmers who expand into pastureland in order to grow more soy, sugarcane, and other crops. Technological advances that allow higher-productivity agriculture could thus help stem deforestation. Indeed, to a large extent, recent reductions in deforestation appear to be a result of improvements in agricultural productivity.[196]

Fortunately, Brazil already has a robust system for agricultural innovation, including a well-established (though sometimes fraught) ability to absorb international technology. Brazilian agricultural productivity has increased by 168 percent since 1976, and the trend continues today.[197] These gains are no doubt due in part to the country's system of agricultural innovation, which is founded on the state-owned EMBRAPA, as well as on strong university-based agricultural science research. EMBRAPA has an annual budget of more than roughly $1 billion and supports both R&D and the commercialization of technology.[198] Its collaborations with researchers from the U.S. Department of Agriculture (USDA) and companies such as BASF and Novozymes testify to the quality of its research. The presence of such a strong engine of domestic innovation helps ensure that crops important to Brazil but not widely grown elsewhere receive adequate attention. And the presence of large agricultural multinationals such as ADM, Cargill, and Bunge, and the growth of large Brazilian firms, helps facilitate international technology flows. But if smaller family farms continue to exist in large numbers—a tendency that has underpinnings in legitimate social goals—international technology diffusion in large parts of the agriculture sector will inevitably become more challenging.

There are also significant IPR challenges associated with agricultural technology. Unlike with clean energy technologies, which are difficult to copy and whose costs normally include little intellectual property, agricultural biotechnology can make use of a great deal of expensive intellectual property and be relatively easy to copy (much like

pharmaceuticals). The case of Monsanto RoundUp Ready (RR) soybeans in Brazil is illustrative. Engineered to be resistant to RoundUp pesticides, RR soybeans allow farmers to use more powerful pesticides and hence increase their yields. Following a judge's decision (since reversed) to ban herbicide-resistant soybeans, "Brazilian farmers turned to Argentina for illegal imports of the Monsanto seed," depriving Monsanto of royalties for the use of its intellectual property.[199] The company found it difficult to stop the flow of these imports thanks to a combination of hard-to-control technology and the Brazilian government's lack of interest in enforcing Monsanto's patent rights. Today, though, Monsanto is able to collect royalties on 80 percent of the RR seeds sold in Brazil, a figure that others in the industry never imagined possible. The CTC, for its part, protects its own intellectual property by using satellite images to identify where its patented strains of sugarcane has been planted and ensure that the growers are paying royalties. While they still find it challenging, these biotech leaders have found ways to ensure significant returns from their intellectual property.

Agricultural and ranching-related biotechnology also provides opportunities to curb emissions that extend beyond deforestation. The spread of crops that are more compatible with no-till agriculture, for example, might help increase the use of that practice. The adoption of special vaccines, meanwhile, could curb methane emissions from cattle. These innovations should be spread by the same mix of mechanisms that help promote productivity-enhancing agricultural biotechnology.

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Cover Photo: The Thanet Offshore Wind Farm off the Kent coast in southern England on September 23, 2010. Thanet farm is the world's largest operational offshore wind farm (Stefan Wermuth/Courtesy of Reuters).

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